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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 3, PP. 103–114
FIGS. 1–5, TABLES 1–3, DECEMBER, 1944

GRAIN ANALYSES OF MINERALS OF SAND SIZE IN BALL MILLS

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University of Rochester

ABSTRACT

Progress in studying sedimentary rocks in *thin sections* would be greatly facilitated if the rates of change in the size, roundness, and sphericity of various minerals in rotating drums were determined by measuring size in diameters, not by screening, and the frequency by (percent of) number, not by weight. These should be two dimensional measurements.

A start was made by crushing specimens of four minerals (quartz, microcline, tourmaline and garnet), screened to sand size and rotated dry in glass bottles supplied with three ordinary marbles at 150 RPM, to a total of 180,000 revolutions, or 31.5 kilometers. Small samples, taken from these ball mills periodically via a microsplitter, were measured microscopically. These data were slightly modified by smoothing and replotted as frequency-distribution curves and as cumulative curves. The roundness and sphericity of the grains were determined by direct comparison with patterns slightly modified from those of Krumbein and Rittenhouse. The results are shown graphically. The plotting of the data of the initial samples results in symmetrical frequency-distribution curves (bell shaped) with one peak. After a short time in the rotating ball mills, a secondary peak is developed in the small size ranges, and the primary peak is reduced and shifted toward small sizes. This increases the sknewness and lowers the sorting. The originally angular grains become slightly rounded and the sphericity increases somewhat. Ultimately the primary peak is destroyed and the secondary peak becomes dominant. The skewness at the start is close to zero, rapidly increases, then slowly decreases. This characteristic is apparently a transitory condition and it seems reasonable to suppose that it may be applied in some cases to natural sediments.

The quartz is reduced in size at the fastest rate, the microcline next, followed by tourmaline, and last by garnet. The Mohs hardness does not seem to be the dominant or controlling factor. The brittleness of the quartz, the cleavage of the microcline, and the toughness of the other two seem to be influential.

Very small grains are rarely rounded, the larger grains more. The degree of roundness, without specifying the size, means very little; the two are interrelated.

These results are the product of mechanical abrasion, not of solution. In nature, solution is an additional process in size reduction, roundness, etc.

INTRODUCTION

Grain size analyses of the minerals of sedimentary rocks in *thin sections* call for further knowledge on the rates of the reduction in size, the change in the roundness, and in the sphericity of mineral grains of sand size in *two dimensions*. Most studies of the wear in rotating drums have been confined in the past (8, 9, 11, 14, 15, 17, 18, 23, 24, 28, 29, 30, 32) to gravel and cobble sizes, and have stressed some one particular aspect of the various problems. Still they do not supply the answers to some of the questions raised by the author's experience with thin section studies of sedimentary rocks. The methods of measuring size and frequency of most of these investigators are not applicable to microscopic studies because the size was determined by screening, and the frequency by weight. Thin section studies require size in diameters, preferably as nominal sectional diameters (27) and the frequency by number of grains.

Most of these investigators attempted to imitate nature. They used water in the rotating drum and used either rock fragments or a mixture of minerals at a time. This introduces a number of uncontrollable variables.

The present study was conducted upon the following principles:

(A) Water is a solvent (24, p. 105) of some minerals which produce some rounding.

(B) Water produces a mud which coats and pads the large grains with the small grains and which

retards the rate of change. Consequently no water was used.

(C) The investigation was confined to one mineral at a time.

(D) Mixed samples can be well studied later.

(E) Frequency-distribution curves, as well as cumulative curves, were plotted. The former are more effective in showing the changes as abrasion continued, as the shifting of the peaks (modes) are more striking in their behavior than the changes in the curvature of the cumulative curves.

EQUIPMENT

Two washing machine wringer rolls, 29.4 cm. long and 5.4 cm. in diameter were mounted parallel to each other, 9.5 cm. apart, center to center, and driven by belts and reducing pulleys by an electric motor. Four glass bottles, with metal tops with an outside diameter of 5.8 cm. and an inside diameter of 5.6 cm., 6.4 cm. in height, were each supplied with three ordinary glass marbles varying in weight from 5.2943 to 4.0472 grams each. The bottles thus became ball mills. These bottles were placed on their sides on the rollers and rotated at a speed of 150 RPM.

TABLE 1. *Data of Ball Mills, 150 RPM*

Minutes	Revolutions	Distance, Meters
100	15,000	2,625
200	30,000	5,250
300	45,000	7,875
400	60,000	10,500
500	75,000	13,125
600	90,000	15,750
700	105,000	18,375
800	120,000	21,000
900	135,000	23,625
1000	150,000	26,250
1100	165,000	28,875
1200	180,000	31,500

METHOD

The minerals were crushed by a hammer on a steel block, magnetically cleaned, and sized by a standard set of screens. The original sample was minus 40 to plus 60 mesh in size. Even though screened alike the frequency-distribution curves of the four were not identical due to the differences in the shapes of the minerals. This characteristic of screening has been the subject of much discussion (31).

TABLE 2. *Initial Sample*

Mineral	Mode, mm.
Quartz	0.45
Microcline	0.38
Tourmaline	0.35
Garnet	0.43

BEHAVIOR OF GRAINS IN BALL MILLS

In the rotating bottles, the marbles rolled in fairly stationary positions. Many mineral fragments were carried entirely around; most of them, however, jostled together and flowed in fine streams between and under the marbles. This resulted in four rings of frosted glass on the inside of the bottles. Fracturing appeared to be more important than grinding. The difference between these appears to be one of degree, not of kind; it is the size of the chips, large for "fracturing," small for "grinding."

MICROSPLITTER

As a small amount was extracted from the total load in each ball mill from time to time, a microsplitter was devised to provide a representative sample. This consists of the rapid rotation of the bottom pan of the set of screens on a vertical axis and pouring the entire mineral load (minus the marbles) through a glass funnel into the revolving pan. The centrifugal force piled up the mineral grains against the side of the pan. A complete, though narrow, segment of this ring of powder was removed by a knife blade and mounted on a microscopic slide in mineral oil.

MEASUREMENTS OF SIZE

The size of the mineral grains was

measured in terms of the nominal sectional diameter in millimeters (27), in two dimensions by the diaphragm method (2) previously described. The choice of the individual fragments was controlled by a mechanical stage, using the cross wire of the occular of the microscope as a line of intercept. In this way the personal factor was greatly reduced. The number of grains per each class interval was recorded by Veeder-Root counters, 150 to 200 grains per mount were measured. A scale with twelve class intervals (3, pp. 261–263) was used. Repeated runs have demonstrated that they can be essentially duplicated. They show that the particular microsplit was very effective.

The initial sample furnished symmetrical single peak curves (bell-shape). Only a few minutes in a rotating bottle, however, produced many small chips which in terms of number, not by weight, produce a new peak in the small size ranges. As wear continued the primary peak diminished in height and slowly migrated towards the small sizes. Meanwhile the secondary peak grew in height and, like the other, slowly moved toward minute sizes. After 1200 minutes of rotation, 180,000 revolutions, 31.5 kilometers, the primary peak is all but gone and the curve consists of the secondary peak with excessive skewness. The long "tail" of the majority of the frequency-distribution curves represents, of course, a comparatively few large fragments. By continued wear the "tail" will be gradually eliminated. If the bottles were rotated a longer time the skewness would be reduced. This study suggests that skewness represents a transitory condition. This is apparently true even though no additions nor subtractions were made. In nature, sorting under the conditions of an open system, the skewness would be more rapidly destroyed by the separation of the extreme sizes; the large grains would be left behind with the transportation of the small grains to a different locality.

POSITION OF ORIGIN OF CURVES

Examination of many histograms, frequency-distribution polygons, frequency-distribution curves, and cumulative curves of sediments reveal that many have the zero to the right, while corresponding plots in books on statistical methods (5, 7, 19, and 25) have the point of origin to the left. The latter position is customary in neighboring sciences and is here adopted for the sake of uniformity.

TREATMENT OF RAW DATA

The number of grains, per class interval, were calculated into per cent and plotted as frequency-distribution polygons. These were smoothed (with due respect to a consistency of area maintained by the use of a polar planimeter), producing frequency-distribution curves. Smoothing of the curves is justified as grain sizes constitute a continuous series. The differences between the polygons and the curves "is not . . . real . . . but is due to accidental conditions of sampling. In other words . . . frequencies . . . conform to the low of distribution represented by the . . . probability curve" (7, p. 226).

The curves for successive times of rotation were compared and the trends of the shifting of the positions, in terms of size, of the peaks (modes) were noted and on plotting they were modified, usually only slightly, to produce a smooth curve.

In a like manner the heights (percentage) of the peaks were plotted and smoothed. See Figure 5A and 5B.

The data were further modified by eliminating the differences in the values of the modes due to screening, so all had the same value.

By accepting the above changes as representing a close approach to the truth, new frequency-distribution curves were constructed and the data read from them were regarded as superior to the original. These provided the basis for cumulative curves used to determine the median and the quartiles.

ROUNDNESS AND SPHERICITY

These properties of the mineral grains were determined by inspection of stand-

ards drawn by Krumbein (15) and Rittenhouse (20). The outlines of these patterns were transferred from the original publications, with enlargement, to a long strip of tracing cloth mounted on rollers and viewed by a camera lucida. Thus the image of the grain was matched directly with the image of the standards. It was necessary to modify slightly the roundness patterns of Krumbein to adapt them to fragments of *minerals*, as the original set was made for rock particles. Furthermore it was necessary to insert finer divisions for the least round ranges. Krumbein's scale is .1, .2, .3 and so on up to .9. The revised scale has roundness values of .11, .13, .15, .17, .19, .21, .23, .25, .27, .29, .31, .33, .35, .37, and .39 as well. As is well known (9), small grains are usually less round (more angular) than large ones, hence the degree of roundness and sphericity were measured for each interval class size. "It should be realized that in any sediment the particles below dimension of about 1/10 mm. exhibit little or no rounding. . . ." (26). Giles (12, p. 103) says of the St. Peter sandstone, that "the angularity . . . showed a constant increase with increasing fineness of grains." These results of this study are shown as curves, figures 1–4, lower right corners. They are the result of measuring between a hundred and two hundred grains and constructing scatter diagrams from which the curves were drawn. The curves show the trends and should not be regarded as precise.

SKEWNESS AND SORTING

The significance of skewness of sediments is imperfectly known (13, p. 220); there is no agreement about the choice of the formula for the calculation of the value of this characteristic. The formula advocated by Bowley (6, pp. 110–117) was selected:

$$Sk = \frac{(Q_3 - \text{Median}) - (\text{Median} - Q_1)}{\frac{1}{2}(Q_3 - Q_1)}.$$

See Figure 5F. The coefficient of sorting is that of Trask (quoted by 13, p. 231):

$$So = \sqrt{Q_3 - Q_1}\ .$$

See Figure 5E. Both of these formulas require the use of cumulative curves.

FREQUENCY-DISTRIBUTION CURVES

Multiple peaked frequency-distribution curves from measurements on thin sections have interested me for some time (1,4). They are relatively quite common when the frequency is by number. They were interpreted in the papers referred to as the result of either a mixture of two or more sources of sediments or to the lack of sorting. It is clear, however, that double peak curves can be produced artificially as the result of wear in the ball mills. No additions or substitutions were made during the entire experiment except for the small amounts extracted for microscopic measurements. In other words, these minerals were studied in a closed system. This is a common concept among igneous rock petrographers.

Microcline.—The microcline used was a pegmatitic microcline microperthite from Spruce Pine, North Carolina. Its composition is approximately Mic_{85} Ab_{10} An_5. It fractured readily under blows of the hammer with the production of many rhombic plates bounded with the striking cleavages of (001) and (010). The tiny fragments are long and narrow, with a low sphericity running from 0.3 to 0.5. The corners of the unrolled specimens are sharp and very angular with the lowest possible roundness value on the scale used (0.11). Due to the perfect cleavage in two directions, the microcline flakes spread on a microscopic slide have a preferred orientation. In other words, the measurements, size, roundness, and sphericity, of these fragments are those of oriented grains. Furthermore they are two dimensional measurements as well. Different values would have been obtained if these microscopic samples had been treated with Canada balsam, kollolith, or bakelite (21, 22) and thin sectioned. This was not done. The problems

of measuring the true size in two versus three dimensions with various orientations remains uninvestigated.

These fragments were examined under polarized light (except the garnet) in order to avoid measuring chips of glass worn from the bottles and the marbles. It was observed that the values varied slightly depending upon whether transmitted polarized light or transmitted plane light (upper nicol out), or reflected light (Leitz Ultropac lamp) was used. The last method did not give strictly two dimensional results as the outlines of the fragments were composites of various layers. Plane transmitted light gave the grains a flatter appearance, but reveals thin edges or "fins" which are invisible with polarized light due to the low polarizing colors of these thin edges. These observations are not important in size and sphericity measurements but are very significant in the determination of roundness. Further work on these factors seems desirable.

The prominent cleavage of the microcline, providing lines of weakness, prevents this mineral from attaining any appreciable degree of roundness and sphericity. Cleavage rather than the relative Mohs hardness of microcline seems to determine the low values as compared with those of quartz.

The rate of size reduction of these minerals with continued wear in the ball mills can be best appreciated by the size position of the primary peak at specified times. See Figure 5C. In this graph the initial sizes have been reconstructed to be the same and hence the differences they show are the results of the physical characteristics of the minerals.

Quartz.—The quartz was a pale pink, milky variety from a vein near Port Henry, New York. It splintered readily under the hammer with the development of many conchoidal curved surfaces. By comparison with the standards of roundness it was slightly less than that of the feldspar. Microscopic observation revealed that the conchoidal fracture of the quartz produced fragments less angular. This characteristic raises the question whether each and every mineral should have its own set of roundness standards. Several such sets were constructed from camera lucida sketches. For this study, however, the sets of patterns for the four minerals were combined. A definite conclusion about this matter was not reached.

In spite of the splintery nature of the quartz, more rounding of the larger grains occurred than was the case of the microcline. This is in inverse to the Mohs hardness. Also, the sphericity of the larger grains of the quartz became slightly higher than the microcline, especially after a thousand minutes of rolling.

It is an interesting question whether quartz grains from a granite would show any differences in behavior.

Tourmaline.—Pale green tourmaline from San Diego County, California, was used. The tourmaline gave the lowest value of the position of the primary peak and likewise the sphericity is the lowest of the four. Perhaps the two are related. The rate of reduction of size of the tourmaline appears to be less than that of the quartz. The roundness is less as well.

Garnet.—Garnet from Gore Mountain, Warren County, New York, was used. It is a common commerical abrasive. Its rate of size reduction is least of all, but became more round than any other mineral.

St. Peter Sandstone.—The four minerals were crushed to the most anuglar possible condition. It does not necessarily follow, however, that clastic sediments start from this condition. Consequently clastic grains of well rounded quartz were used in an additional series of runs. A specimen of St. Peter sandstone from Klondike, Missouri, was found to be ideal material. This rock has long had the reputation of possessing quartz grains with a high perfection of roundness. Drake (10) voiced the opinion that the high order of "uniformity has been heretofore greatly over-estimated . . ." Giles (12) confirms this view. The St.

Peter sandstone investigated by Giles was from widely separated localities in northern Arkansas (12). The mode of Giles' data (based upon weight percentage) is about 0.25 mm., while mine is at 0.275 mm. (percent by number). In thin sections the mode is at 0.24 mm. (nominal sectional diameter). In roundness, as loose fragments, the small grains are angular (0.11–0.21) but at about .175 mm. in size the roundness rises to 0.6 or more. With treatment in a ball mill the roundness of the intermediate sized grains is at once reduced; only the unfractured large grains have high roundness values. With continued rolling the wear soon reduces the roundness of all fragments to values to 0.3 or below, then the value rises slightly as rolling continues and the fractured fragments are re-rounded. At 1200 minutes of rotation, the curves of roundness and sphericity of grains of the St. Peter sandstone are essentially the same as the originally angular pink vein quartz at the same number of minutes. The intial roundness of the clastic grains of these minerals is not long maintained in the ball mill.

SUMMARY

This study of sized angular fragments of four minerals of sand size in glass bottle ball mills rotated 180,000 revolutions without water, provided material for two dimensional microscopic measurements of grain size, roundness, and sphericity. The size distribution was based upon nominal sectional diameters, in percentage, by number, using twelve class intervals. The roundness was determined by direct comparison with Krumbein's published patterns, slightly modified and extended for mineral fragments. The sphericity of the grains was likewise accomplished by matching the grains with Rittenhouse's set of outlines.

Screened mineral fragments before treatment in the ball mills form single peak symmetrical frequency-distribution curves. The position, in terms of size, of the modes (peaks) are not exactly the same, due to differences in shapes of crushed fragments with different cleavages. A few minutes in a ball mill profoundly affected the shape of the frequency-distribution curve; the primary peak is reduced in height with the development of a secondary peak in the small size range. Continued rotation of the mills moved these peaks towards the smaller sizes. The height (percentage) of the primary peak is continuously reduced, while that of the secondary peak, naturally, increases. At about 1200 minutes of rolling the primary peak has all but disappeared. The skewness meanwhile becomes very pronounced. It is reasonable to assume that with continued rotation of the ball mills not only would the primary peak be destroyed but the "tail" in the large size ranges would be eliminated as well, reducing the skewness eventually to zero. It is concluded that skewness is a temporary or a transitory condition. It may be this can be directly applied to natural sediments. Two peak curves have been produced by rolling these minerals in ball mills as closed systems. Sedimentary rocks are products of open systems. The separation of large grains from small, or vice versa; in other words, if sorting occurs it would produce single peak curves. Plotting of the positions of the primary peak, corrected for initial differences in grain size, for a number of minutes (distance) show that they are asymptotic in character as demonstrated by Krumbein (14). The order of reduction in size, from the largest to the least, is as follows:

TABLE 3

Mineral	Quartz	Microcline	Tourmaline	Garnet
Mohs Hardness	7	6	7.5	7

It is necessary to remember that these results are for ball mills *without* water. Solubility of the minerals varies in different solutions. Certainly roundness of some, if not many minerals, can be assigned in part to solubility in nature.

There is need for the study of the shape of frequency-distribution curves in terms of microscopic two dimensional measurements of various minerals in thin sections. The measurements should be by size in terms of nominal sectional diameter and the frequency by number, not by weight.

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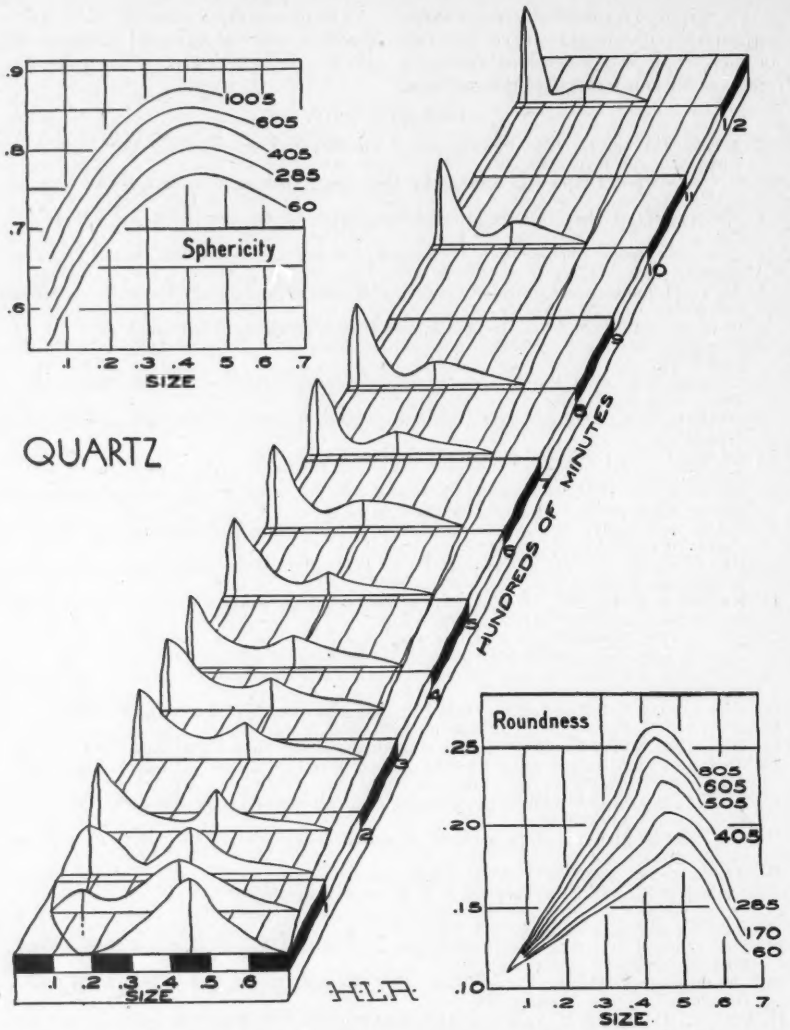

FIG. 1.—Quartz. Central figure; frequency-distribution curves, per cent by number, of grains plotted against size, as nominal sectional diameter, millimeters, for number of minutes *rotated dry in ball mill, 150* revolutions per minute.

Upper left: sphericity, based upon patterns of Rittenhouse, and plotted from scatter diagrams. Numbers refer to length of time rotated.

Lower right: roundness, based upon patterns of Krumbein. Numbers refer to length of time rotated.

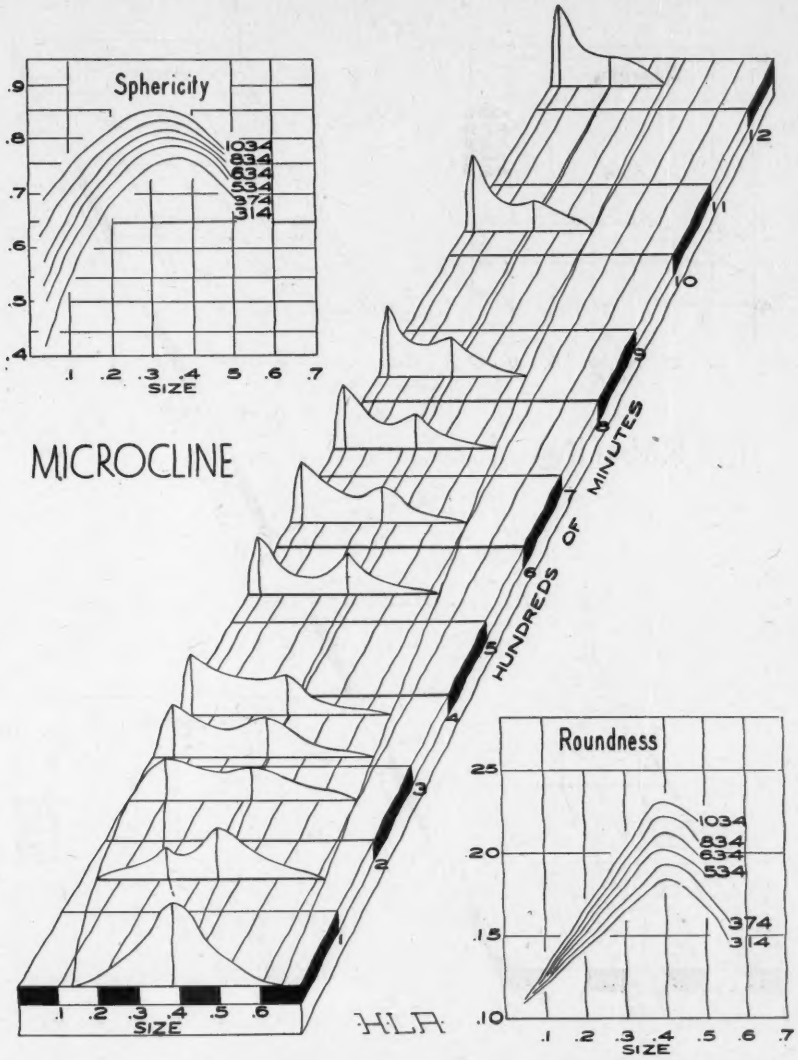

FIG. 2.—Microcline. Central figure; frequency-distribution curves, per cent by number of grains plotted against size, millimeters, as nominal sectional diameter, for number of minutes *rotated dry in ball mill.*

Upper left: sphericity, based upon patterns of Rittenhouse, and plotted from scatter diagrams. Numbers refer to length of time rotated.

Lower right: roundness, based upon patterns of Krumbein. Numbers refer to length of time rotated.

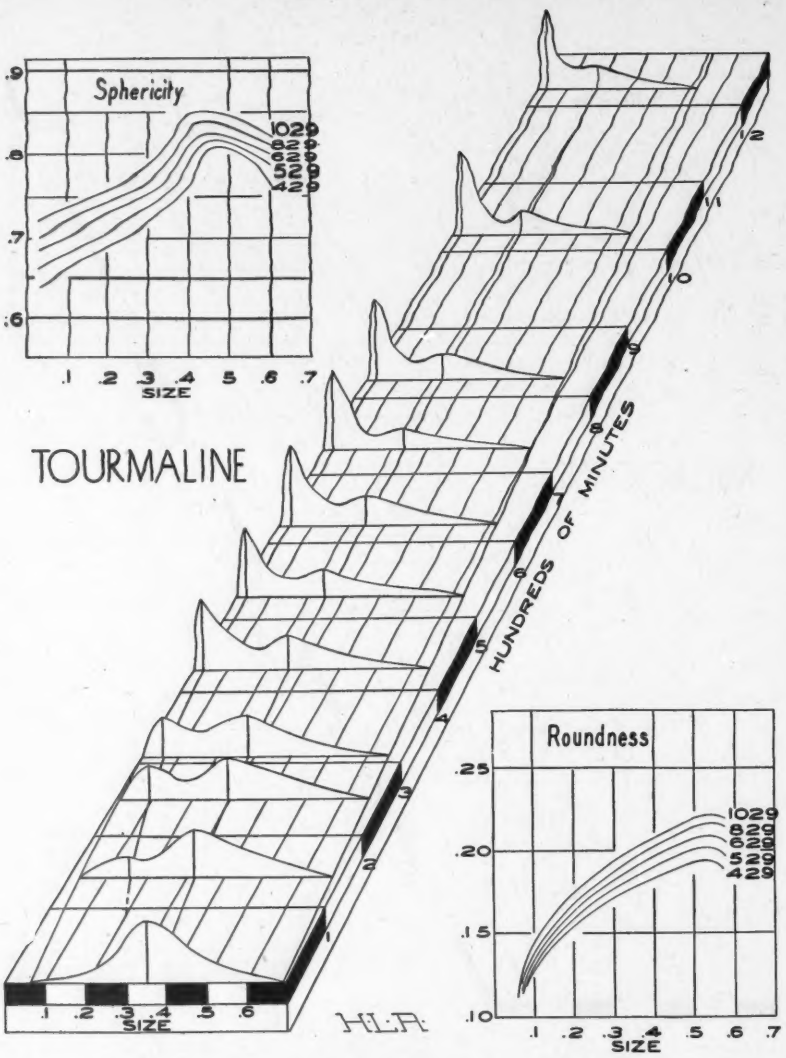

FIG. 3.—Tourmaline. Central figure; frequency-distribution curves, per cent by number of grains, plotted against size, millimeters, as nominal sectional diameter, for number of minutes rotated dry in ball mill.

Upper left: sphericity, based upon patterns of Rittenhouse, and plotted from scatter diagrams. Numbers refer to length of time rotated.

Lower right: roundness based upon patterns of Krumbein. Numbers refer to length of time rotated.

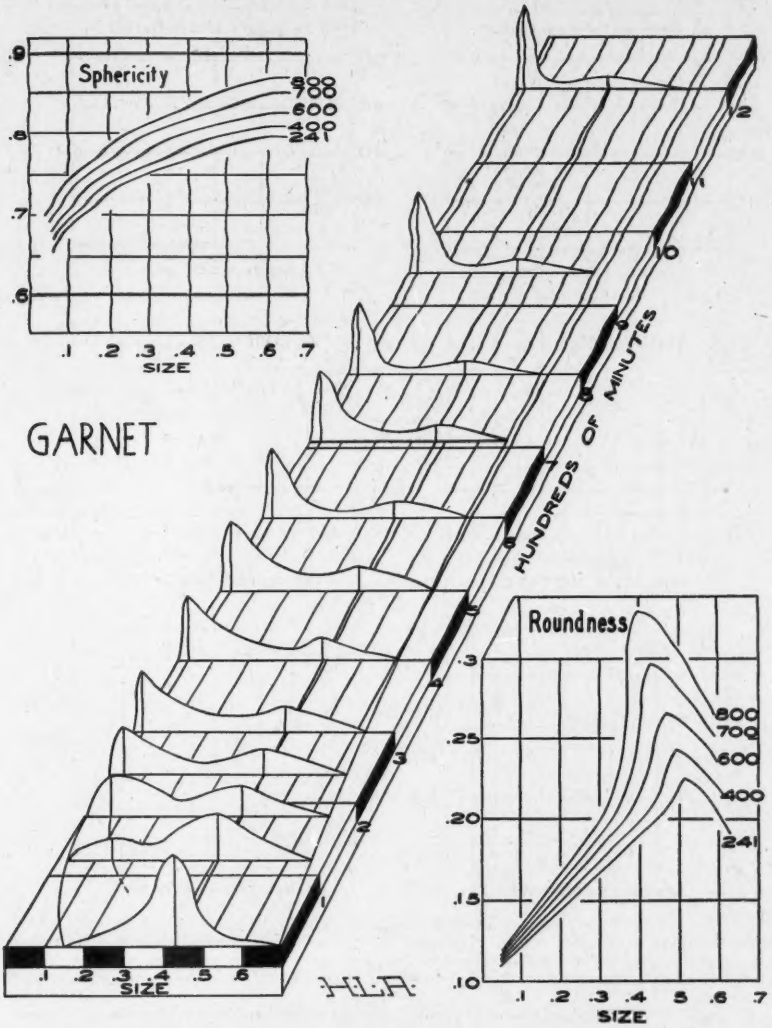

FIG. 4.—Garnet. Central figure; frequency-distribution curves, per cent by number of grains, plotted against size millimeters, as nominal sectional diameter, for number of minutes rotated dry in ball mill, 150 revolutions per minute.

Upper left: sphericity, based upon patterns of Rittenhouse, and plotted from scatter diagrams. Numbers refer to length of time rotated.

Lower right: roundness, based upon patterns of Krumbein. Numbers refer to time rotated.

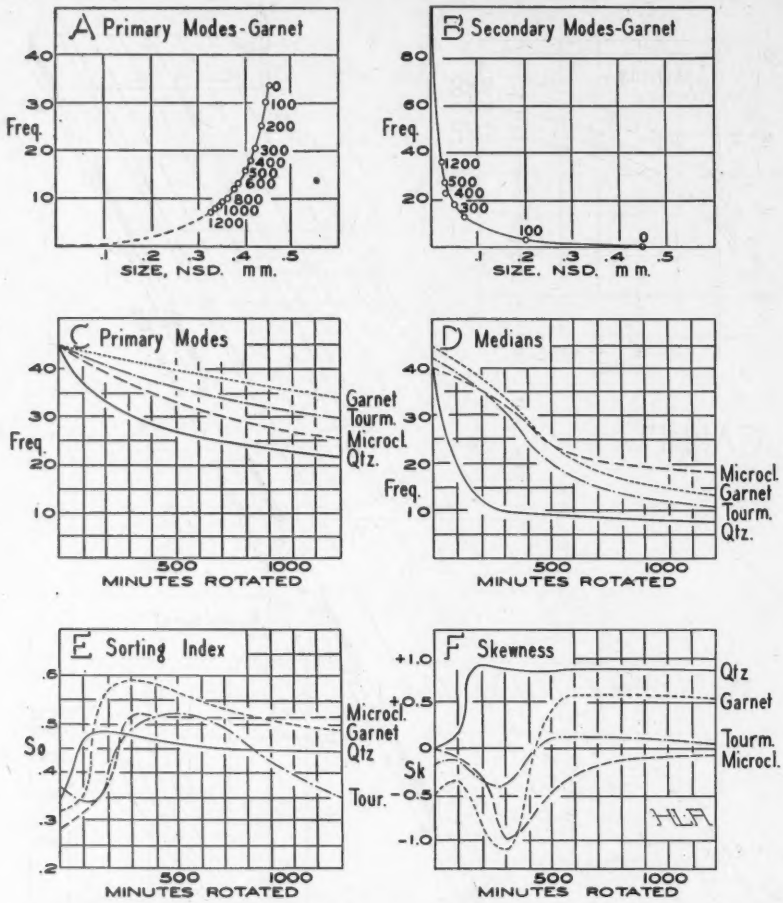

FIG. 5.—Curves based upon re-smoothed original data.

A. Positions of primary modes of garnet. Size, nominal sectional diameter, against frequency, per cent of number of grains. Numbers refer to number of minutes rotated dry in ball mill. Curve shows the ultimate limit of position after infinite time, namely zero size.

B. Positions of secondary modes of garnet, showing extensions from zero per cent, .45 mm. size to 100 per cent and zero size.

C. Comparison of the primary modes for the four minerals.

D. Comparison of the medians of the four minerals drawn from cumulative curves.

E. Coefficient of sorting. Formula: $So = \sqrt{Q_3 - Q_1}$.

F. Skewness. Formula: $Sk = \dfrac{(Q_3 - Md) - (Md - Q_1)}{1/2\, Q_3 - Q_1}$

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 3, PP. 115–124
FIGS. 1–6, TABLE 1, DECEMBER, 1944

DEPOSITION OF SEDIMENT IN POOL NO. 15 AT ROCK ISLAND, ILLINOIS

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ABSTRACT

The Upper Mississippi Valley canalization project was authorized by Congress in 1930. The construction of 24 navigation dams in addition to the power dams already in operation at Fort Snelling, Minnesota (Dam No. 1) and at Koekuk, Iowa (Dam No. 19) enables a 9-foot channel to be maintained from St. Paul, Minnesota to St. Louis, Missouri. The new structures are low-head, movable, roller-gate dams, a type especially designed to reduce deposition in the pools. During excessive high-water stages the dam is out of operation and open-river conditions allow the current to make a clean sweep.

A re-survey of the pool bottom upstream from Dam 15 at Rock Island, Illinois, in October, 1943, on the same ranges as were surveyed in August, 1938, and in June, 1930, before the dam started operation, indicates that in the 10-year period: (1) deposition was active during the early stages of the pool's existence, mainly due to a shift of the channel, and (2) during the later stages scour exceeded deposition. The discharge of the river was abnormally high in the later years.

Pool 15 is located in a gorge where the slope is steep and there is no flood plain and therefore this study does not yield facts or conclusions which can be applied equally to all the dams. It may be stated that there will be no excessive silting like there was in the early years of the pool. The periodic high stages of water will sweep out the deposits and the abnormally steep gradient causes a fast flow which will not allow for much deposition. Long periods of low flow necessitating an almost closed dam are favorable for deposition but it must be remembered that low velocities transport much less sediment.

BACKGROUND HISTORY

The Upper Mississippi River is that portion of the stream above the mouth of the Missouri River, about 15 miles upstream from the city of St. Louis, Missouri. The river level drops approximately 326 feet in this 673 mile stretch and the natural river slope is 0.45 foot per mile; this slope is uniform except for rapids at Minneapolis, LeClaire, Rock Island, and Keokuk.

The Mississippi River has long served as an important artery of commerce. However, with the development of larger and more powerful boats the Upper Mississippi River's usefulness was doomed unless steps were taken to provide a deeper channel such as is in existence on the lower part of the river. Legislation in 1907 was passed for the establishment of a 6-foot channel but this proved inadequate and it was in 1930 that Congress authorized the Upper Mississippi River Canalization Project. The objective was to provide a 9-foot channel from Minneapolis, Minnesota, to St. Louis, Missouri, by constructing a series of locks and dams throughout the length of the Upper Mississippi River. The upper river was to be converted into a descending stairway of river pools. All structures used in this series were built in the ten years following the authorization except two which were built for commerical power purposes some time before the beginning of the project. Dam No. 19 at Keokuk, Iowa, was completed in 1913 and Dam No. 1 at Minneapolis (sometimes called the Ford Dam) was consturcted in 1917.

In 1930 the project began by starting work on Dam No. 2 at Hastings, Minnesota, and the following year work began on Dam No. 15 at Rock Island, Illinois. The dam at Hastings was completed in 1932 and the Rock Island dam in March, 1934. The successive years saw the com-

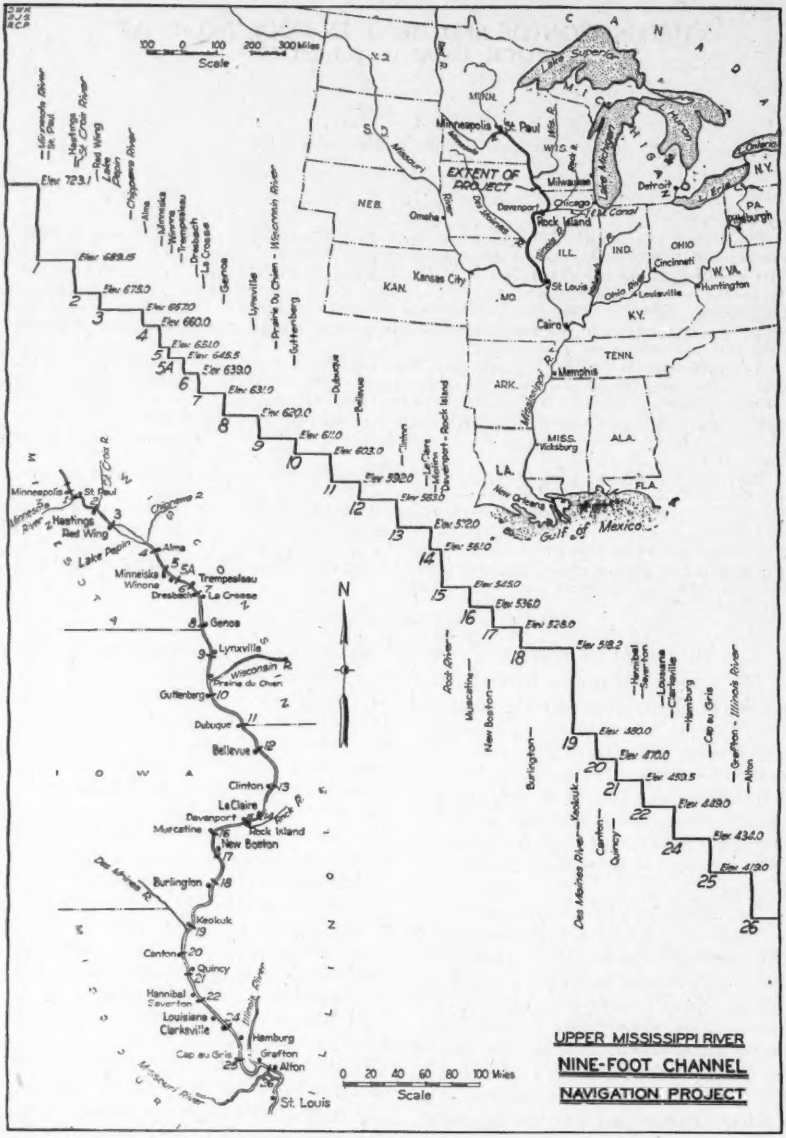

FIG. 1.—Upper Mississippi River Nine-foot Channel Navigation Project.

pletion of the other 22 dams in the series: three being completed in 1935, three in 1936, five in 1937, seven in 1938, three in 1939 and one in 1940. The project was completed in 1940, since which a nine-foot depth of water has been maintained from Minneapolis, Minnesota to St. Louis, Missouri (fig. 1.).

The design of the dams for the Upper Mississippi River was influenced by several natural conditions. High dams were not the solution inasmuch as behind the low banks of the river lay the wide flood plain which is highly cultivated and also supports many towns, railroad lines, highways, etc. High flood discharges necessitated movable dams which will not obstruct the passage of flood waters. Some types of movable dams can be lowered to the bed of the river by a derrick and the water and traffic pass unobstructed over the top when the channel has enough natural depth for navigation. The Upper Mississippi does not have such natural depths during enough of the season of navigation to warrant construction of this type of dam. Also flood changes are not so great or so rapid as compared with other streams and ice conditions are such as not to favor the construction of the movable type dam which folds down to the river bed.

In the light of existing conditions, roller gate or Tainter gate dams, or a combination of both, are the best adapted for this project. In the former, the roller gates, large steel cylinders, roll on tracks, slightly inclined from the vertical, and can be raised or lowered thus controlling the amount of water discharged underneath. The Tainter gate is simpler, being only a water-tight segment of a cylinder with the convex side upstream which is lowered or raised to control the flow of the water.

All of the dams in the Upper Mississippi River Canalization Project are of this movable type except the two commercial structures mentioned above. These 22 new dams can be opened or closed at will and the dams pass about the same quantity of water as is flowing in the river at any given time. In times of flood, the gates are raised as the water stage rises until they are finally clear of the water and the water passes through with little obstruction. These dams, therefore, are not suitable for the continuous production of power nor can they serve for flood control. The flood heights above the dam are not increased very much and because of the natural passage of flood waters, there is little accumulation of sediment in the pools above the dam.

The problem of deposition or silting in these pools has been an active question. The stationary power dams built prior to 1930 give evidence of the enormous depositing power of the river. Dam No. 1 does not create much of a problem because it is almost at the head of the river and there are not many tributaries upstream from it. Dam No. 19, however, is a different question. When it was built in 1913 it had a storage capacity of about 500,000 acre feet; but 15 years later it had reduced its storage capacity 23% by silting and sounding in 1936 showed the storage capacity had been reduced by 30%. Most of the dams have been in operation too short a time for accurate estimates of the deposition in the pools, but Dam 15 created a pool which has been in existence over 10 years and a study of deposition in this pool appeared worthwhile.

NATURE OF THE PROBLEM

Construction of a dam across the Mississippi River at Rock Island, Illinois, created a pool known as pool 15. This study deals with the deposition of sediment in this pool.

Soundings were taken on twelve ranges on the river in the lower end of the pool (fig. 2). The ranges were established by the Corps of Engineers, U. S. Army, in 1930 and soundings were taken by them in that year and again in 1938. The soundings taken by the author in 1943 were made with a lead line at an average of about 60 feet apart. Position on the range was determined by triangulation after

the sounding stops were spotted with a transit. The profiles constructed were compared with the profiles taken on the same ranges in 1930, before the construction of the dam, and in 1938, after the dam was in operation.

DESCRIPTION OF THE AREA

Description of Dam and Locks.—The dam at Rock Island, Illinois is a roller gate dam 1,203 feet, 2½ inches long, all of which is movable. There are eleven roller gates, each 109 feet long. Nine of the rollers have a damming height of 21 feet, 9 inches. These two gates, called skimmer gates, are operated to pass water one foot in depth over the top while one-half foot of water passes underneath. All roller gates can be raised to clear the water level when necessary. Dam No. 15 is unique in that it is composed of roller gates its entire length. No earth dams are necessary on each side of the roller portion because there is no flood plain.

There are twin locks on the left bank (south side) of the river. One lock is 600 feet in length and 110 feet wide and the other is 360 feet long and 110 feet wide. Both locks have a lift of 16 feet.

Description of Pool No. 15.—Pool No. 15 is 10.4 miles in length, the shortest pool on the Upper River with the exception of the diminutive Pool No. 1, has an average width of 3,100 feet and has a surface area of 4,000 acres. The pool is located in a gorge, a feature which is very important in this discussion.

Most of the Upper Mississippi River flows in a large valley partly filled with more than 100 feet of glacial material in places; however, from LeClaire, Iowa, about 20 miles upstream from Dam 15, to Muscatine, Iowa, 30 miles down stream, the river flows in a narrow valley cut in rock. It is in this valley that Pool 15 as well as portions of Pools 14 and 16 are located. In this stretch the flow velocities are high because of the steep gradient of 1.2 feet per mile, about three times normal.

The pool now formed has an elevation of 561 feet (mean sea level, 4th G.A., 1912). This level above the dam is maintained as long as the tail water stage be-

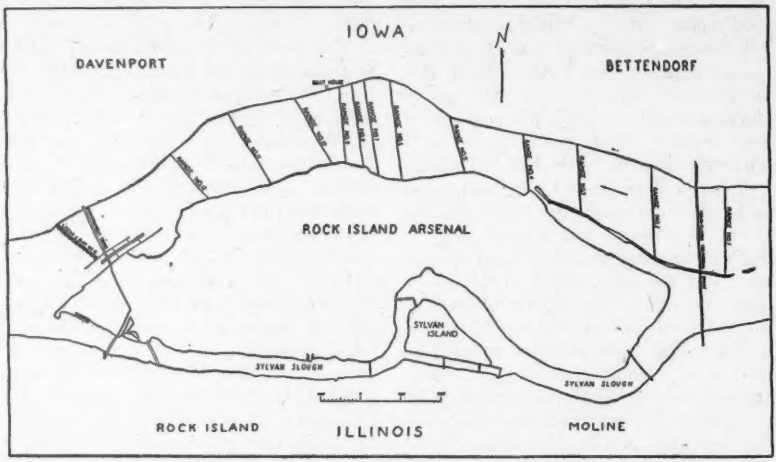

FIG. 2.—Index map showing location of Ranges in Lower End of Pool No. 15.

low the dam is lower than 552.5. When tail water stage rises of 552.5 feet, but is still below 555.5 feet, the pool level is lowered to 560.0, and when tail water stage rises to 558.2 the pool is drained and the roller gates raised above the water surface.

The divided channel in the lower end of pool 15 is a unique feature. This allows part of the flow to escape control of Dam No. 15. This small diversion is termed Sylvan Slough (fig. 2). The slough is controlled by two power dams of the fixed type. They pass very little water: at low water stage about 7,000 cubic feet per second and at high water stage about 2,500 cubic feet per second.

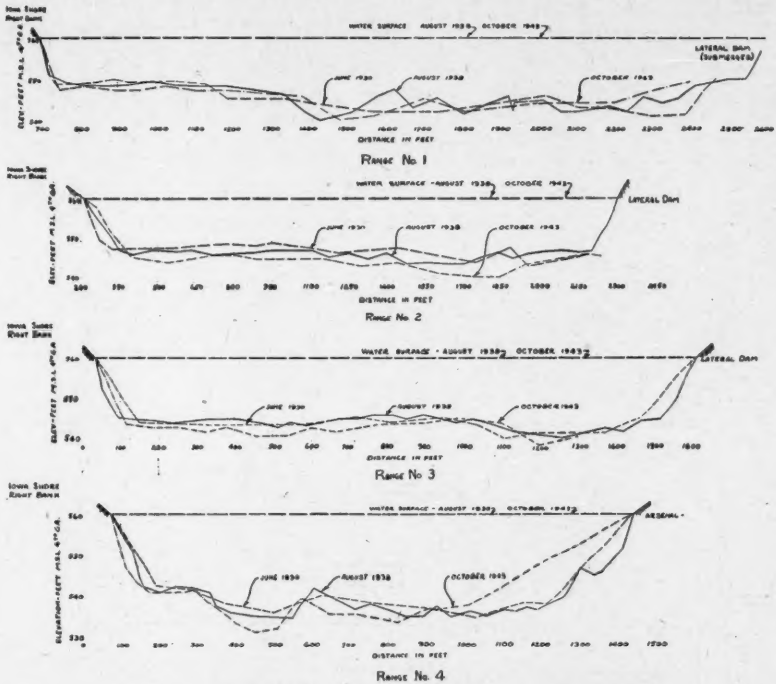

FIG. 3.—Comparative cross sections of lower end of Pool 15.

FORMATION OF THE POOL

The formation of the pool placed many feet of water over this old Rock Island Rapids area. This at first caused a change in the channel. The old channel under open river conditions was along the Iowa shore in the vicinity of the Lindsey Park Boat Club (fig. 2). The channel was guided by rock but undoubtedly weaker rock existed in the boat club area. With the pool in existence, the old channel was abandoned, and the river took the shortest distance through the Rapids reach. This left the old channel in deep, quiet water.

FEATURES OF THE 1938 SOUNDINGS

A series of soundings were taken in 1938 and the resulting profiles or cross sections were plotted over soundings taken in 1930. The location of these ranges can be seen in the index map (fig. 2).

Treating each range individually, the following changes are noted (figs. 3, 4, 5.):

Range 1. Scour predominant over deposition and most of the scour taking place on the south side.

Range 2. Scour again most active but not so localized.

Range 7. Continuing of the major deposition on the north side in the still water area. The range shows the greatest deposition.

Range 8. Still much deposition on the north side.

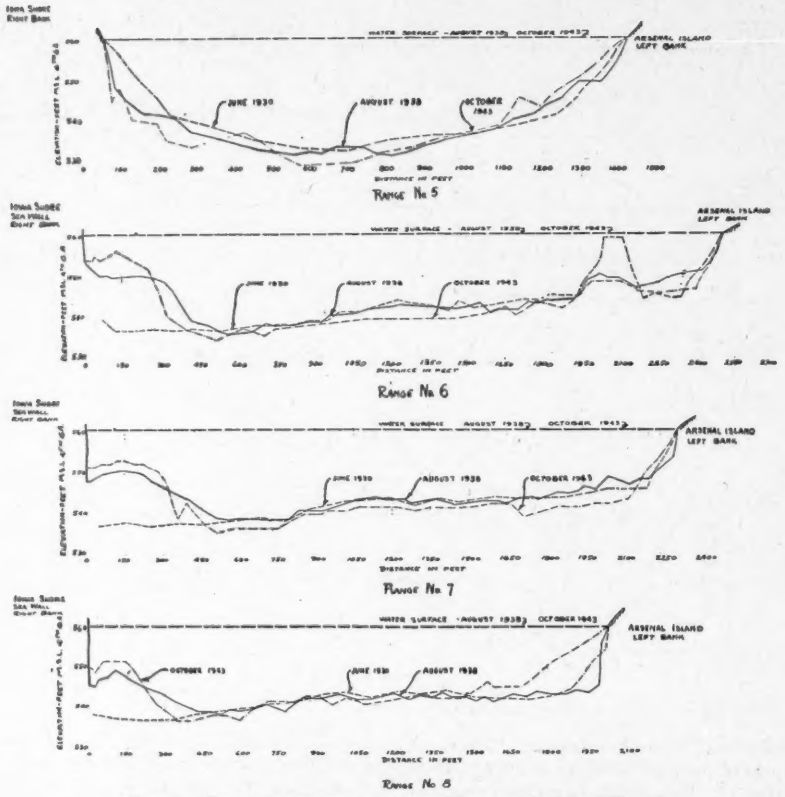

FIG. 4.—Comparative cross sections of lower end of Pool No. 15.

Range 3. Deposition a little greater than scour.

Range 4. Scour predominating.

Range 5. Scour predominating with most erosion on the north side.

Range 6. Beginning of the major deposition on the north side in the old channel. This range shows the second highest depositional figure.

Range 9. Deposition on the north side.

Range 10. Small deposition; rather evenly distributed.

Range 11. Deposition mostly on the south side.

Range 12. Small deposition; rather evenly distributed.

Taking the area as a unit, deposition

was predominant over scour (Table 1). During the first four and one-half years of the pool's existence, 26,139,622 cubic feet of sediment were deposited while 8,367,852 cubic feet were scoured out, showing that 17,771,770 cubic feet of sediment were deposited over and above the volume scoured out. Scour occurred in the upper end of the reach but in the vicinity of the boat club, the old channel, deposition was very heavy. The bulk of the deposition can probably be attributed to the changing of the channel.

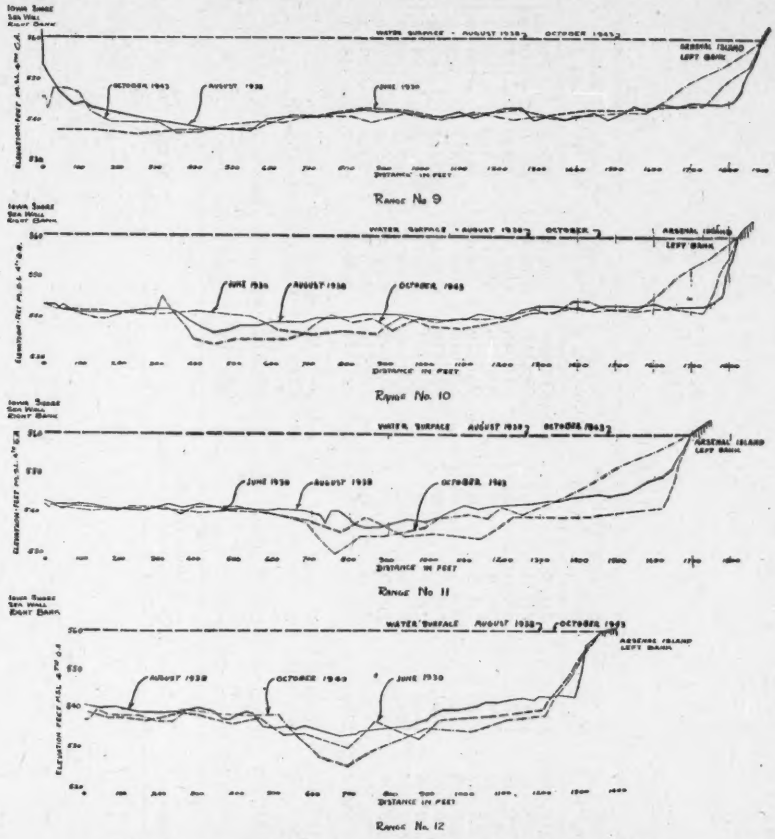

FIG. 5.—Comparative cross sections of lower end of Pool No. 15.

FEATURES OF THE 1943 SOUNDINGS

In 1943, five years later, another series of soundings were taken and the profiles were plotted over those taken by the Corps of Engineers, U. S. Army, in 1930 and 1938. The 1943 soundings were taken in October and the pool elevation was 561 feet, the same as in the 1938 soundings.

The following is a survey of the activity which occurred on the individual ranges since 1938 (figs. 3, 4, 5).

TABLE 1

Range	Balance Sq. Ft.	Balance Cu. Ft.	Scour Sq. Ft.	Deposition Sq. Ft.	Balance Sq. Ft.	Balance Cu. Ft.	Scour Sq. Ft.	Deposition Sq. Ft.	Balance Sq. Ft.	Balance Cu. Ft.
1.	− 148.2	− 257,950	2371.2	1447.8	− 923.4	−1,615,950	1664.4	889.2	− 775.2	−1,358,000
2.	− 759.0	−1,409,150	5434.0	1375.0	−4059.0	−7,509,150	3960.0	660.0	−3300.0	−6,100,000
3.	+ 302.4	+ 501,472	1789.2	336.0	−1453.2	−2,404,046	1965.6	210.0	−1755.6	−2,905,518
4.	− 1134.0	−1,735,120	2998.8	705.6	−2293.2	−3,508,596	1984.5	825.3	−1159.2	−1,773,476
5.	− 3046.4	−4,965,632	4800.0	748.8	−4051.2	−6,603,456	1824.0	819.2	−1004.8	−1,637,824
6.	+ 8122.9	−8,366,375	4340.8	9408.8	+5068.0	+5,220,040	4003.2	948.8	−3054.4	−3,146,032
7.	+10213.5	+4,566,375	3052.5	11561.0	+8508.5	+3,828,825	3998.5	2359.5	−1639.0	− 737,550
8.	+ 3487.4	+1,360,398	1162.8	5288.7	+4125.9	+1,609,101	1264.8	1902.3	+ 637.5	+ 248,703
9.	+ 5278.2	+2,691,882	1043.1	3972.9	+2929.8	+1,494,198	2815.8	467.4	−2348.4	−1,197,684
10.	+ 1465.0	+1,603,175	1810.0	1505.0	− 305.0	− 334,975	2235.0	465.0	−1770.0	−1,938,150
11.	+ 2631.2	+4,090,516	726.8	1361.6	+ 634.8	+ 986,114	2070.0	73.6	−1996.4	−3,104,402
12.	+ 1897.2	+2,959,732	2294.0	737.8	+1556.2	−2,427,572	3682.8	229.4	−3453.4	−5,387,304
Total deposit		+26,139,622	Total cubic feet scour			24,403,745	Total cubic feet scour			29,285,940
Total scour		− 8,367,852	Total cubic feet deposit			13,138,278	Total cubic feet deposition			248,703
Bal.: total cu. ft. deposit		+17,771,770	Balance: total cu. ft. scour			11,265,467	Balance: total cu. ft. scour			29,037,237
Deposit: cu. yards		658,217	Scour: cubic yards			402,409	Scour: cubic yards			1,075,438
Comparison of 1930 and 1938 soundings			Comparison of 1930 and 1943 soundings				Comparison of 1938 and 1943 soundings			

Range 1. Scour exceeding deposition.
Range 2. This range shows the greatest scour.
Range 3. Evenly distributed activity with scour dominating.
Range 4. Much deposition on the south side and much scour on the north side.
Range 5. Scour, mostly limited to the north side.
Range 6. Some scour and some deposition on the north side with scour dominating. The sediments of the first five years were slightly cut into but were built up higher near the north side.
Range 7. Scour and deposition on north side. More deposition on this range than on any of the other but scour still slightly dominant.
Range 8. Second most in quantity of deposition. The only range in which deposition is more than scour.
Range 9. Dominance of scour fairly evenly distributed.
Range 10. Scour most in north center.
Range 11. Scour mostly in center as the channel narrows.
Range 12. Much scour in the center of the range.

The area as a whole, as indicated by these 1943 soundings, suffered a total scour of 29,285,940 cubic feet while deposition was only 248,703 cubic feet. Thus a balance of 29,037,237 cubic feet of scour (Table 1).

Why so much scour in the last instance while deposition was dominant in the first five years? One must take into consideration that the deposition, as the result of the changing of channel, would occur in the early years of a pool's existence and after this deposition had occurred it would merely be a see-saw arrangement between deposition and scour.

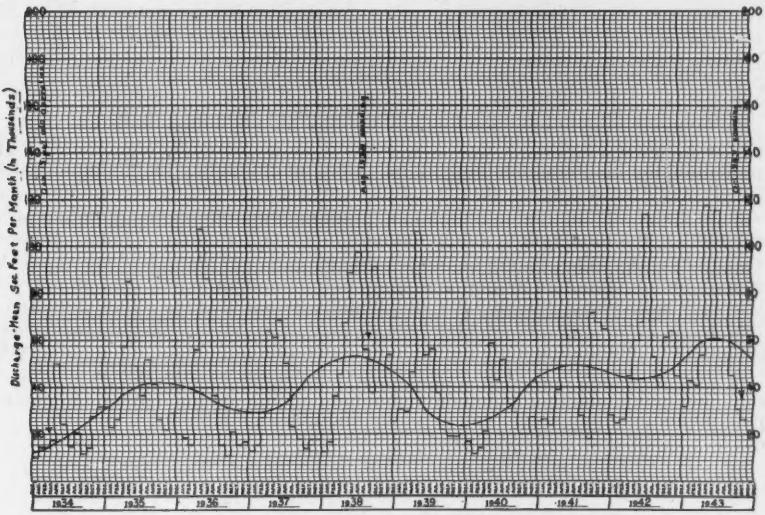

FIG. 6.—Monthly and yearly mean discharge of the Mississippi River at Pool 15 from 1934–1943.

A very important point that must be considered in this discussion is the variation in the flow of the river. As shown by figure 6, the yearly mean is rising over the years and in 1943 the mean was the highest. What is even more important

are the high discharges over a short period of time, for they tend to sweep out deposits. In flood stage the rollers of the dam are not in operation and open river conditions prevail. This allows the swift water to sweep out sediment of years of accumulation.

Figure 6 shows that exceptionally high water prevailed in some of the years between 1938 and 1943. Most important, and it cannot be overemphasized, is the flow of the river just before the soundings in 1943 were taken. The flow figures are the highest monthly mean in the whole pool history up to this time.

CONCLUSIONS

1. Deposition in the early years of the pool's existence was largely due to the pool formation and the change of channel. This can be seen by the great localization of the deposits. Scour was dominant on the first three ranges, as it was in the 1943 profiles. The balance of the activity was in favor of deposition in the first five years as approximately 17,771,770 cubic feet of sediment accumulated.

2. The 1943 soundings show that the early deposition stage of the pool was past and a fluctuating equilibrium was reached. Scour was perhaps a little bit higher than average because of the phenomenally high discharge, especially in April and June of 1943. The amount of scour over deposition was approximately 29,000,000 cubic feet.

3. Future. There will be no excessive silting like there was in the early years of the pool. The periodic high stages of water will sweep out the deposits and the abnormally steep gradient causing a fast flow will not allow for much deposition. Long periods of low flow, necessitating an almost closed dam, would be favorable but it must be remembered that low velocities transport much less sediment.

ACKNOWLEDGMENTS

The author wishes to thank Mr. Len Carlson of the U. S. Engineers for his constant aid and suggestions throughout the work. Dr. A. C. Trowbridge was very helpful and patient in the organization of the material. Judge Edward Turnbaugh of Moline kindly provided the author with a boat and also served as pilot. Mr. Dale Lambert plotted the positions with the transit during the operations and Miss Mary Jean Hill assisted in the recording of the soundings. The drafting was done by Mr. Hedquist, Mr. Ebb and Miss O'Brien.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 3, PP. 125–130
FIGS. 1–2, DECEMBER, 1944

RED RIVER MINERAL PROVENANCE, TAOS COUNTY, NEW MEXICO

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and
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ABSTRACT

The Red River mineral provenance is located in the Taos Range which comprises the western part of the Sangre de Cristo Mountains, Taos County, New Mexico. Detrital materials are derived from Pre-Cambrian gneisses, schists and granites, Carboniferous sediments, Tertiary igneous rocks, and contact zones formed by the igneous rocks. Hand specimens, thin sections, optical properties, and inclusions were used to identify the individual source rock. Practically all the heavy minerals as well as quartz are derived from the Pre-Cambrian rocks. The Tertiary igneous rocks supply an abundance of quartz, some feldspar, and a minor quantity of magnetite, epidote, zircon, rutile and mica. The contact zones contain molybdenite, fluorite, pyrite, chalcopyrite and mica.

INTRODUCTION

Red River, a large mountain stream about 30 miles in length, is located within the confines of Taos County, New Mexico. The entire drainage basin, a region of high relief at an elevation ranging from 6,000 to 12,000 feet above sea, is located in the western part of the Sangre de Cristo Mountains. These mountains split into two ranges near the New Mexico-Colorado boundary of which the Taos Range is to the west and the Cimmaron Range to the east. Red River from its source near the center of Taos Range follows a northerly direction as far as Red River City where it swings to the west and, after emerging from the Red River Canyon, joins the Rio Grande a few miles west of the town of Questa.

Rock exposures in the Red River basin include the Pre-Cambrian Basement Complex, Carboniferous sediments, and recent intrusives and extrusives. The basement rocks consisting of gneisses, schists and granites are covered by Carboniferous sediments in the upper part of the basin and by igneous rocks in the lower part. The chief Pre-Cambrian exposures are in the central part of the basin and in the Red River Canyon where the overlying igneous cover has been removed. This basement rock, a huge batholith, constitutes the core of most of the ranges.

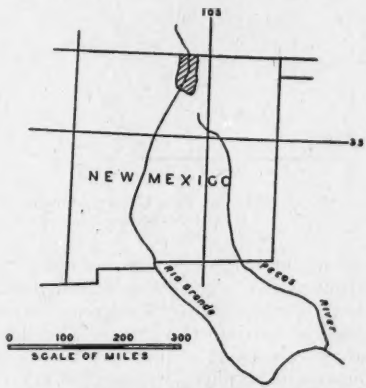

FIG. 1.—Map of New Mexico showing position of Taos County.

Extending from the divide between Red River and Pueblo Creek northward along the eastern margin of the Red River basis are sediments which have been described by Gruner as Carboniferous. Near its source, Red River has

cut a deep canyon exposing sandstones, limestones, shales, conglomerates and arkosic materials. There is good evidence, as pointed out by Gruner and others, that during Pennsylvanian time Pre-Cambrian rocks were undergoing erosion and supplied the major part of the Carboniferous sediments.

The igneous rock cover in the lower part of the basin is the result of two different lava movements. The exact time of these movements is not definitely known but evidence points to a comparatively recent origin. These igneous rocks have been divided by Lindgren, Graton and Gordon into two groups. The older group, consisting of intrusive masses of monzonite porphyry, was assigned as pre-Tertiary, whereas the younger group, including andesite intrusives and rhyolite flows, is dated as late-Tertiary.

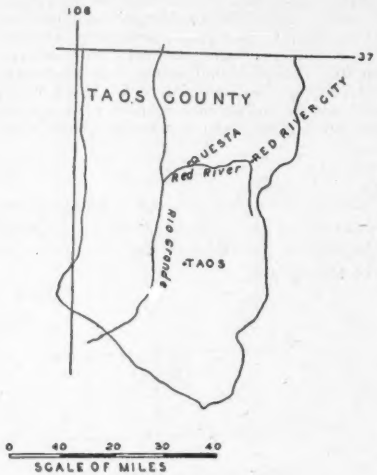

FIG. 2.—Map of Taos County showing Red River basin.

METHOD OF PROCEDURE

Field work, other than collecting samples, consisted of general observations concerning the character of the stream load, type of weathering and rock outcrops. In the laboratory thin sections and detrital materials were utilized. From each sample 25 grams of sand were sieved and weighed to determine the size grade. Heavy minerals were removed from each grade by bromoform. Identification and extent of alteration of the minerals was determined with the aid of binocular and polarizing microscopes.

MINERAL RESOURCES

The chief mineral resources of the Red River area include molybdenite, fluorite, and gold. Molybdenite in limited quantities is associated with gold ores, but the commercial deposits are concentrated in Sulphur Gulch about seven miles below Red River City. In this area, one of the largest molybdenum producing regions of the world, the ore is almost pure molybdenite and is found chiefly as veins (Northrop) along joints. This ore is associated with igneous rocks which have been described by Larson and Ross as granodiorite porphyry.

Fluorite, found in approximately the same areas as molybdenite, occurs chiefly as veins, some of which are several inches in this thickness. Even though this mineral is available in large quantities it is not utilized commercially.

Production of gold, centered about Red River City, reached its peak near the close of the nineteenth century. Some of the metal was secured from placers but the chief source was from veins which range in thickness from a few inches to six feet. It has been pointed out by Lindgren, Graton and Gordon that these veins are found in the monzonite porphyry and are thought to be related to the rhyolites. Gold mining at the present time is limited to small individual prospects and placers.

DETRITAL MINERALS

In the Red River mineral provenance practically all sediments are derived from Pre-Cambrian gneisses, schists and granites, carboniferous sediments, Tertiary igneous rocks consisting of monzonite porphyries and rhyolite flows, and ig-

neous contact zones. Hand specimens, thin sections, heavy mineral suites, optical properties and inclusions were all employed to determine the individual source rock. These criteria show the Pre-Cambrian rocks to be an important source. They supply, other than quartz, practically all the hornblende, diopside, andalusite, anatase, garnet, and tourmaline, a major portion of the magnetite, rutile and mica, and a minor quantity of the hematite.

It is difficult to determine minerals that are characteristic of the Carboniferous. Thin sections, hand specimens and detritals failed to reveal minerals that are not supplied by the Pre-Cambrian rocks. However, compared to the materials derived directly from the Pre-Cambrian rocks, some Carboniferous minerals exhibit a greater degree of erosional wear and a slight difference in the alteration products.

The Tertiary igneous rocks provide an abundance of quartz, some feldspar, and a minor quantity of magnetite, zircon and epidote. Associated with the contact zones in the igneous rocks are gold bearing ores, molybdenite, fluorite, pyrite, chalcopyrite, and mica.

The abundance of each of the heavy minerals was determined by percentage in respect to the total number. The heavy minerals in order of abundance are magnetite, diopside, hornblende, hematite, epidote, andalusite, mica, zircon, pyrite, garnet, rutile, anatase, tourmaline, chalcopyrite, fluorite, and molybdenite. Of these the first three make up about 80 per cent of all the heavy minerals. The last eight are each represented by less than one per cent of the heavy mineral total.

DESCRIPTION OF THE MINERALS

Magnetite—Magnetite is one of the abundant minerals and is represented chiefly as irregular grains with hackly fracture. Occasional grain exhibits minute shiny facets. The luster varies from metallic black to dull grey. Various degrees of alteration were noted. Smeo grains are in an early stage of decay as shown in the rust-colored surface streaks, whereas others have been almost completely changed to hematite. Most of the magnetite is concentrated in sediments with a diameter range below $\frac{1}{4}$ mm. Some of the magnetite is derived from Tertiary igneous rocks but the chief source is from the Pre-Cambrian. The abundance of this mineral is marked by a progressive increase downstream.

Diopside—About 20 per cent of the heavy minerals are diopside. It occurs chiefly as prismatic grains that range in color from light green to white. The decrease in the intensity of the green color in the altered grains suggests that the color change is from green to white. Most grains are partially altered, probably to chloritic matter, thus producing a cloudy appearance. The altered materials are unevenly distributed but there is a tendency for them to be concentrated along the cracks that traverse the grains. Small opaque inclusions are common. In the course of Red River the abundance of this mineral decreases downstream from 38 to 20 per cent.

Hornblende—Approximately 20 per cent of the heavy minerals in the Red River area are hornblende. It is present chiefly as irregular cleavage, fragments with frayed ends. Various shades of green, as brownish-green, dark-green, blue-green and light-green were noted. Of these the blue-green and light-green varieties are most abundant. In most grains the color density decreases from the center toward the margins. Well developed striae are present on some of the unaltered fragments. Small dark, opaque, inclusions are numerous. Alteration products, probably chloritic matter, are concentrated on the edges and frayed ends of some grains. On others a rust-colored material either hematite or limonite has accumulated. Pre-Cambrian schists and granites constitute the chief source for the hornblende. Decrease in the abundance of hornblende downstream from the source is from 33 to 21 per cent.

Hematite—All gradations ranging from yellow limonitic materials to typical hematite are present in the Red River sediments. This mineral is found as irregular, earthy, yellow to reddish-brown grains; pseudomorphs, chiefly yellowish brown cubes; and coating on sand grains. The magnetic property varies with the color, being weakest in the yellowish-brown variety. Some dark colored grains appear to be altered products from magnetite. Hematite comprises about ten per cent of the heavy minerals and attains its maximum abundance in the lower part of the basin.

Epidote—Less than six per cent of the heavy minerals in the Red River area are epidote. It occurs chiefly as irregular grains that range in color from greenish-yellow to light-yellow. Inclusions and alteration products are limited. Maximum pleochroism is in the greenish-yellow variety. Well developed ringed interference tints are conspicuous. Since the chief source of epidote are Tertiary igneous rocks, its maximum abundance is in the lower part of the Red River Canyon.

Micas—The micas, including muscovite and biotite, constitute slightly more than one per cent of the heavy mineral total. Biotite is the most common mica. These minerals are supplied by the Pre-Cambrian schists and granites and by the contact zones in the Tertiary igneous rocks. They attain their maximum abundance in the upper part of the basin. *Muscovite* is present in two forms; the common variety consists of thin transparent flakes with inclusions; less common are the clouded grains which may be leached biotite. Inclusions are varied, some are needle-like grains, possibly zircon, others consist of dark colored materials that resemble biotite. The transparent flakes are unaltered and show a well centered biaxial figure. *Biotite* occurs as irregular cleavage flakes with jagged edges and as well developed hexagonal basal flakes. This mineral is light brown to black except in the altered grains where the color varies from light shades of brown to transparent. Most of the grains contain inclusions some are rod-like transparent crystals, others are irregular and opaque. Halos border some of the crystal inclusions. Pleochroism is weak and most of the grains are weakly magnetic.

Zircon—Tertiary igneous rocks in the central and lower portions of the basin constitute the principal source for the zircon. It represents about one per cent of the heavy mineral total. The color ranges from colorless to purple. The most prevalent type of grain is the colorless prismatic form with pyramidal terminations. Fractured grains are rare. Cavities and well developed crystal inclusions are present in the transparent grains. Most of the crystal inclusions are colorless prismatic minerals with an index of refraction lower than zircon. Zoning was observed in a few grains. Zircon is concentrated in sediments with a diameter range below 1/8 mm.

Pyrite—The maximum concentration of pyrite is in the lower part of the Red River Canyon. It occurs in two forms; the common form consists of well developed cubes and dodecahedrons; less common are irregular aggregates. The prevailing color is brass-yellow but many of the grains are tarnished. Well developed striae were noted on the cubes. The occurrence of pyrite in solution cavities suggests an epigenetic origin for the mineral.

Garnet—Only one variety of garnet, almandite, is represented. It is found chiefly as irregular fractured grains with conchoidal fracture. Crystal faces were recognized on a few fragments. Practically all grains contain crystal inclusions. Some are dark and opaque, probably magnetite, others are transparent, probably quartz. Most of the grains are isotropic, but a few show anomalous interference tints. Almandite is of minor importance in the Red River basin and it is derived from Pre-Cambrian rocks.

Rutile—Rutile is represented by two varieties. Most common are the red and reddish-brown fractured grains that are widely distributed in the Red River

area. Less common are the yellow grains that are present only in the central and lower portions of the basin. No inclusions or alteration products were noted. The red and reddish-brown variety is weakly pleochroic. Oblique striations are well developed on a few of the grains. Pre-Cambrian rocks are the chief source of the red and reddish-brown variety; yellow rutile is derived from Tertiary igneous rocks.

Anatase—The occurrence of anatase is equally divided between simple and compound pyramidal forms and tabular grains. Well developed striae were present on some of the grains, but others exhibit geometric zoning. The color ranges from indigo-blue to black. Large thick grains are nearly opaque and weakly pleochroic. A few light colored inclusions, probably quartz, were noted. In the Red River area it appears to be primary and to be derived from Pre-Cambrian rocks. Anatase is concentrated in the 1/8 to 1/16 mm. grade and attains its maximum abundance near the source of the stream.

Tourmaline—In the Red River area only the brown variety of tourmaline is represented. It occurs as prismatic grains with basal termination and irregular fragments. Striations are present on some of the fragments. This mineral is highly pleochroic and has the characteristic parallel extinction of the tourmalines. Most of the tourmaline is in the diameter range below $\frac{1}{4}$ mm. Pre-Cambrian rocks appear to be the only source for this mineral.

Chalcopyrite—Chalcopyrite is represented by a few brass colored tetrahedrons. It is associated with pyrite and no doubt they have a similar origin. The luster is metallic and even the smallest grains are opaque. Chalcopyrite differs from pyrite by the deeper yellow color and hardness. Contact zones in the Tertiary igneous rocks are the chief source of this mineral.

Fluorite—The greatest concentration of fluorite is in Sulphur Gulch where it is present in veins several inches in thickness. Minor deposits are found in the contact zones associated with gold bearing ores. Detrital fluorite is represented by octahedral cleavage flakes and irregular grains. The color ranges from transparent to blue and it may vary in different parts of the same grain. Cavity inclusions are common.

Molybdenite—Two minerals of molybdenum, molybdenite and molybdite, are represented. *Molybdenite* in commercial quantities exists in Sulphur Gulch where it occurs as veins, disseminated grains, and nearly pure foliated masses. Other minor deposits are associated with gold ores. The mineral *molybdite* is widely distributed throughout Red River Canyon and it is recognized by the sulphur yellow color. This mineral, according to Tarr, is formed in the oxidized portion of the ore body. In the Red River area detrital molybdite consists of earthy grains and incrustations.

Quartz—This mineral is represented chiefly as angular to sub-angular elongated, pitted grains which are partially coated with iron oxide. Due to the parting and parallel lamellae some grains resemble plagioclase. On the bases of optical properties and inclusions the quartz grains in this area are divided into three groups. In the largest group, probably igneous quartz, the grains are characterized by concentric ring interference colors, no strain shadows, and numerous inclusions of dark colored minerals and bubbles. A second group includes grains that exhibit undulose extinction and possess acicular inclusions which appear to be the mineral sillimanite. This type of quartz is described by Krynine as metamorphic. The grains in the third and minor group are transparent and void of inclusions. This quartz is also of igneous origin.

Feldspar—Feldspar is not an important detrital mineral. Orthoclase and plagioclase are represented. Of these the plagioclase group is the most abundant. These minerals occur chiefly as angular fragments. Some are fresh but the majority have undergone some degree of

decay thus presenting a cloudy appearance. No inclusions were noted.

CONCLUSIONS

In the Red River basin the detrital minerals are derived from Pre-Cambrian gneisses, schists and granites, Carboniferous sedimentaries, and comparatively recent monzonite porphyry intrusions and rhyolite extrusives. Practically all hornblende, disopside, andalusite, garnet, anatase and tourmaline were derived from the Pre-Cambrian rocks, but the recent extrusives and intrusives constitute the chief source of the pyrite, chalcopyrite, zircon, molybdenite, fluorite, and epidote. Magnetite, mica, rutile, epidote, and hematite were supplied by both Pre-Cambrian and recent igneous rocks.

The minerals that exhibit some degree of decay include magnetite, hornblende, andalusite, mica and feldspars. Magnetite shows various stages of alteration, ranging from surface rust streaks to grains that have almost completely changed to hematite. Diopside has been changed to produce a cloudy material which is concentrated along the cracks traversing the grains. The edges and frayed ends of the hornblende grains have been altered to form a light colored material. Andalusite presents a turbid appearance due to the formation of sericite. Mica, especially some of the muscovite, has a cloudy appearance and contains dark colored materials. The greyish-white appearance of some of the feldspars suggests alteration to a clay mineral.

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FIGS. 1–4, TABLES 1–3, DECEMBER, 1944

HEAVY MINERAL CORRELATION OF THE FOX HILLS, HELL CREEK, AND CANNONBALL SEDIMENTS, MORTON AND SIOUX COUNTIES, NORTH DAKOTA

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ABSTRACT

The heavy minerals from surface exposures in the Fox Hills, Hell Creek, Ludlow, and Cannonball formations, Morton and Sioux Counties, North Dakota, are studied. Nine mineral zones are established on the basis of heavy mineral frequencies. The first three correspond to lithologic units in the Fox Hills, the third extending to the base of the Breien marine member of the Hell Creek. Zone 4, in the Cannonball River sections, is the lower bed of brown sands in the Breien. Zones 5 and 8 are local. Zone 6 begins in a bentonitic sand in the Breien and extends above the Breien. Zone 7 is in the upper Hell Creek and Ludlow. Zone 9 corresponds to the Cannonball.

The Fox Hills and the Cannonball are characterized by a high percentage of green amphibole. The Hell Creek is differentiated by its epidote, garnet, and sphene content.

INTRODUCTION

Much of North Dakota, South Dakota, Montana, and Wyoming are covered with continental and marine sediments of Upper Cretaceous and Tertiary age. The present work was undertaken in an effort to correlate a restricted portion of these sediments by their heavy mineral content.

The area covered in this report extends south and southwest of Bismarck and Mandan, North Dakota, along the Missouri and Cannonball Rivers. River bluffs and isolated buttes furnished excellent exposures.

STRATIGRAPHY

Upper Cretaceous

Fox Hills

The Fox Hills is the lowermost formation which crops out in the area studied. It consists of (1) a lower horizon of thick-bedded yellowish brown sandstone, with brown concretions and Halymenites; (2) an intermediate horizon of yellow to olive colored sandy, banded shale, in part equivalent to (3); and (3) an upper horizon of gray-white sandstone with concretions.

Hell Creek

The Hell Creek formation consists of buff or gray sand with shale partings, bentonite, and brown and black lignitic shale. The shale partings occur in zones four to eight inches wide and are separated by massive sands two to four feet thick. The individual partings are one-sixteenth to one-eighth inch wide. The Hell Creek contains concretions of marcasite, limonite, and of a black ferruginous, manganese-bearing material. The Breien marine member of the Hell Creek occurs close to the base of the Hell Creek.

Paleocene

Ludlow

The Ludlow formation resembles lithologically the Hell Creek formation but differs from it in containing more persistent lignite beds. In the area studied, the Ludlow consists of chocolate brown

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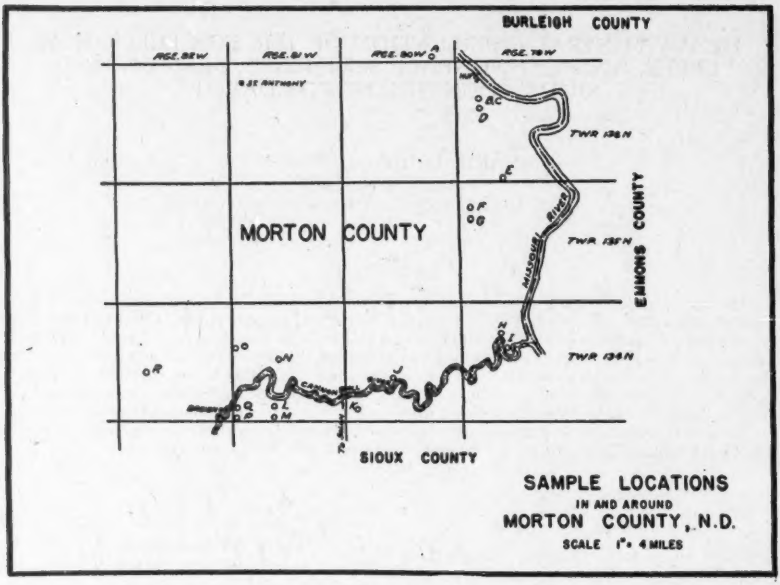

FIG. 1.

lignitic shales, with some black lignite. Charcoal was found in some exposures.

Cannonball

The Cannonball formation consists of buff, yellow, or greenish yellow sandstones and dark gray shales. Its marine character is indicated by the presence of Halymenites. It interfingers with and overlies the Ludlow.

STRUCTURES

In the individual exposures the strata appear to be horizontal, or are cross-bedded, or irregularly bedded, or they fill channels. Hancock (1921, p. 11) and Calvert (1914), in the course of a study of the neighboring lignite fields, determined a dip of a few feet per mile to the northwest. Laird (1942) reports a dip of 15 feet per mile to the northwest. This dip is evident from the mineral zones along the Cannonball and Missouri Rivers, since equivalent zones occur lower in the section to the west and north.

Filled stream channels are narrow, shallow, and mark an erosional unconformity. They may have sharp, steep sides, or may be marked only by an irregular lower level. Channeling is typically developed at locality F. Slump and joint blocks dip into the sides of the channel. The channel filling is irregularly bedded, with rapid variations horizontally and vertically from clay to medium-grained sands. In the middle portion the strata dip from the side toward the center and are cross-bedded. Higher up the initial dip flattens, and the sediments are laid in a shallow spoon-shaped deposit.

Slump along bedding planes occurred while the sediments were being deposited at Section B. At various horizons chunky clay is broken into pieces one to four inches long and one inch thick. These pieces are lying at all angles, in the posi-

tion of small folds, occurring in a single bedding plane. In a zone where buff sands alternate with brown shale partings, folds and drag folds are easily visible. The axial plane is horizontal, but the axis is not constant in direction.

FIELD STUDIES[2]

Section B

S.W. ¼, Sec. 8, T. 136 N., R. 79 W. The section begins on the south side of the bluff at its base.

Hell Creek

1. Sand, fine-grained, and silty clay, buff, fluted, with shale partings. Five samples at 5′ intervals. 24.0′
2. Sand, bentonitic, gray. One sample.
3. Sand, fine-grained, buff, speckled, and gray clay, with shale partings, cross-bedding, and contemporaneous slump. Seven samples at approximate 5′ intervals. 53.0′
4. Shale, brown, bentonite, gray, clay and silty sand, gray. The lower portion contains interbedded bentonitic clay and buff sand; the upper portion is a gray bentonite. One sample. 18.5′

Total thickness Hell Creek 95.5′

Ludlow

5. Brown lignitic shale and loose gray clay with plant remains. Grades into a coaly shale, 11″ thick and 32″ above the base. Gypsum. 14.4′
6. Sand, fine-grained, yellow, with brown shaly partings at the bottom of the bed, gray, concretionary sand in the middle portion of the bed, and yellow sand at the top. One sample. 6.5′

Total thickness Ludlow 20.9′

Cannonball

7. Cover (?) 20.0′
8. Sand, green gray, with brown lignitic partings, marcasite and limonitic concretions, and thin styolitic veinlets and nodules of coarse-grained white gypsum. Four samples. 12.0′
9. Shale, brown, and sandy clay with limonitic stains. Two samples 5′ apart. 20.6′
10. Sand, fine-grained, yellow gray, speckled, with rust stains, and brown to black shaly partings weathering reddish brown on the surface. Fissile black shale. Marcasite nodules and limonitic zones. Halymenites small at base and larger higher in the section. Cross-bedding in middle portion. Topped by a hard concretionary jointed layer with irregular top and bottom. Five samples at 5′ intervals. 29.0′
11. Clay, flaky, shale, gray, cover, and sandy brown or black shale with marcasite concretions. One sample. 43.6′

Total thickness Cannonball 125.2′

Section J

S.E. ¼, Sec. 21, T. 134 N., R. 80 W. Section begins at the edge of the Cannonball River.

Fox Hills

1. Sand, fine- to medium-grained, green to brown, with limonite concretions and staining. Cross-bedded. Halymenites. Four samples at 10′ intervals. 55.0′
2. Sand, fine-grained, brown, with bands of gray clay and some shale. Limonite concretions less abundant. Top of member a cross-bedded and jointed concretionary sand. Three samples at 10′ intervals. 33.0′
3. Sand with clay, bentonitic, gray. Gypsum. 22.0′
4. Sand fine-grained, and interbedded silt, flaky clay, and shale, gray; some brown shale partings; iron-stained; cross-bedded. Concretions cross bedded and jointed. Three samples. 61.3′
5. Clay, silty, gray. 2.2′

Total thickness Fox Hills 173.5′

[2] Five of the 17 localities samples are described. Clay refers to grain size.

Hell Creek

6. Shale, brown lignitic, with some sand and clay. 5.5′
7. Sand, fine-grained, light yellow gray. One sample. 6.0′
8. Clay, gray, silty, with limonitic staining. 4.6′
9. Shale, brown to black lignitic, with sandy clay. 16.2′
10. Sand, fine-grained, silt, clay, buff, with gypsum. Two samples 15′ apart. 26.3′
11. Shale, brown lignitic, with gray silty clay. 6.0′

Total thickness Hell Creek 64.6′

Section L

N.W. ¼, Sec. 33, T. 134 N., R. 81 W. Section begins where the bluffs rise above the floodplane.

Fox Hills

1. Shale, gray, flaky, silty, with sand. Slumped. Base not exposed: A thin band of flaky limonite at top. 8.0′
2. Sand, fine-grained, light gray, with some interbedded bentonitic shale, fluted. Abundant, large coarse-grained concretionary layers. Six samples at 5′ intervals. 32.0′

Total thickness Fox Hills 40.0′

Hell Creek

3. Shale, chocolate, very sandy, and concretionary at bottom; lignitic, fissile toward the top. Channel deposit. Thickness and position variable. Two samples. 3.0′
4. Bentonite, gray, with silicified tree stumps. 2.0′
5. Shale, silty, gray green, with thin ledges of concretions of limonite and marcasite. Toward the top is a black shale with plant remains. 6.0′
6. Sand, very fine-grained, with silt, buff-yellow, marcasitic. Two samples 5′ apart. 8.3′

Breien Marine Member of the Hell Creek

7. Sand, fine-grained, brown, with limonitic chips and with small concretions of limonite. Slumped. Weathered. 2.6′
8. Sand, fine-grained to silt, buff, with marcasite. Two samples.
9. Shale, dark yellow-gray, limonitic, and sandy shale. 14.8′
10. Sand, fine-grained to silt, gray green. Two samples.
11. Bentonite. 1.8′
12. Sand, fine-grained, bentonitic. One sample. 3.3′

Total thickness Hell Creek 41.8′

Section M

Laterally displaced south of L. Section begins on the east side of the butte.

Breien Marine Member of the Hell Creek

1. Sand, very fine-grained, brown, limonitic, weathered, loose. Halymenites abundant on surface. One sample. 6.0′
2. Sand, slightly bentonitic, gray. One sample. 2.0′
3. Bentonite, gray. 2.2′
4. Sand, fine-grained, buff, with gray clay. 4.4′

Undifferentiated Hell Creek

5. Shale, brown lignitic. 2.2′
6. Silty clay, gray, flaky, bentonitic toward top, with limonitic concretions. One sample. 15.3′
6. Shale, brown lignitic. 4.2′
7. Sand, fine-grained, pale yellow or buff, fluted. Three samples at 5′ intervals. 13.8′
8. Shale and silt interbedded. 9.4′
9. Sand, fine-grained, buff, fluted, with flaky shale, buff clay, and brown shale partings. Three samples 5′ apart. 14.1′

Total thickness Hell Creek 73.6′

Section R

Center section 20, T. 134 N., R. 82 W. Section begins on the east side of the butte at the base.

Hell Creek

1. Sand, fine-grained, gray or buff, with silty clay and shale partings,

fluted, compact, with limonitic concretions. Three samples at 5′ intervals. 16.0′

2. *Sand, very fine-grained, silt, clay,* bentonite, shale. 5.0′

3. *Bentonitic clay, sandy toward* top. 18.0′

Total thickness Hell Creek 39.0′

Ludlow

4. Shale, chocolate brown, flaky or fissile, with some buff sand, dark gray clay, and black lignitic shale interbedded. Marcasitic concretions. One sample in sand. 27.0′

Total thickness of Ludlow 27.0′

Cannonball

5. *Sand, medium-grained, yellow,* cross-bedded, topped by a layer of *indurated yellow sand three feet thick.* Four samples at 5′ intervals. 17.0′

Total thickness of Cannonball 17.0′

LABORATORY STUDIES

A preliminary examination of the samples showed that they are well sorted, with a fine- to very fine-grained texture, and contain silt and clay. The silt and clay were decanted until the water remained clear after one minute in a 400 cc. beaker. The dried sand was sieved on a 150 mesh Tyler screen, opening .104 mm., and the portion retained on the sieve was separated by tetrabromoethane, sp. gr. 2.9. The heavy fraction was boiled with a weak solution of hydrochloric acid to destroy the calcite and limonite that act as a cement in some of the samples.

Two hundred and fifty non-opaque minerals were counted, and the ratio between opaque iron ores and the non-opaque minerals was determined, making a total of 500 grains counted when the ratio is 1:1. Tables were computed showing the relative percentages of platy minerals, and opaque and non-opaque minerals, and the non-opaque ones were recomputed to 100%. The mineral frequencies of the non-opaque minerals, especially green amphibole, epidote, and garnet, formed the basis for formulating *nine mineral zones. Table 1,* "Average and Range of Mineral Frequencies" shows the number of samples examined in each zone at each section, the average percentage of each mineral present, and the range over which it occurs in a given zone, at that section. Table 2, "Representative Mineral Frequencies" shows the average percentage of each mineral in a zone and the typical proportions between the varietal forms.

DESCRIPTION OF THE MINERAL SUITE

The heavy mineral fraction may be divided into three groups, the platy minerals, the non-opaque ones, and the opaque iron ores. Selective sorting, rather *than provenance, causes a change in* proportions of each group, since platy *minerals will be floated beyond the non-*opaque ones, which, in turn, are carried farther than the heavier opaque minerals.

The platy minerals are biotite, chlorite, and muscovite. They are widespread in small percentages, but, exceptionally, are found in appreciable quantities in shales and rotten sandstones. Biotite occurs as brown or green pseudohexagonal or irregular basal sections; chlorite, as well rounded, light green basal plates; and muscovite, as splendent pseudohexagonal basal plates.

The opaque iron ores consist of magnetite, ilmenite, and leucoxene intergrown with ilmenite. The grains are equidimensional and subangular.

The non-opaque heavy minerals form the basis for heavy mineral correlation. The characteristics of the various minerals are listed below. The mineral frequency may be found in Tables 2 and 3.

Andalusite occurs in rounded-irregular, and elongated-subangular grains. Pleochroic and non-pleochroic varieties are equally dominant. The former is always fresh, but the latter is occasionally sericitized.

Amphibole is diagnostic for purposes of correlation. It occurs in acicular prisms. There are three types: (1) color-

TABLE 1. *Average and Range of Mineral Frequencies (First figure indicates average,*

	No. of Specimens in each zone	Platy Minerals		Opaque Minerals	Non-opaque Minerals	Non-opaque mineral recomputed to 100%				
		Mica	Chlorite			Andalusite	Amphibole	Clinozoisite	Corundum	Epidote
Section A										
Zone 7	6	1(tr–4)	1(0–1)	44(23–67)	54(32–75)	1(0–2)	2(1–5)	9(5–15)	0	55(48–64)
Zone 6	1	1/2	1/2	52(—)	47(—)	1(—)	11(—)	8(—)	tr(—)	40(—)
Zone 4	5	1(—)	1(0–1)	53(33–70)	45(30–65)	tr(0–2)	18(6–35)	5(1–6)	0	37(26–44)
Section B										
Zone 9	12	3(0–11)	tr(0–2)	26(23–41)	71(59–91)	1(0–3)	49(33–65)	6(3–8)	tr(0–tr)	25(19–32)
Zone 7	10	4(1–10)	2(0–3)	45(33–50)	49(39–63)	1(0–2)	1(0–2)	10(3–18)	tr(0–1)	61(37–68)
Zone 6	3	8(1–18)	1(0–1)	40(28–60)	51(39–62)	1(1–2)	5(3–6)	5(4–6)	0	45(40–48)
Zone 4	2	7(3–11)	2(1–3)	29(—)	62(58–67)	1(0–1)	15(12–17)	4(4–4)	0	48(45–51)
Section D										
Zone 9	4	8(tr–30)	6(tr–11)	25(23–33)	63(25–77)	1(0–3)	54(32–71)	6(1–12)	0	20(14–29)
Zone 7	9	3(1–6)	1(tr–3)	45(33–63)	51(33–65)	tr(0–1)	3(0–6)	12(3–24)	tr(0–1)	46(34–61)
Section E										
Zone 7	2	2(1–2)	tr(0–tr)	53(47–60)	45(39–51)	2(1–2)	8(6–12)	7(5–7)	tr(0–tr)	49(44–54)
Zone 6	2	0	tr(0–tr)	61(55–68)	39(32–45)	1(0–1)	7(6–7)	3(1–5)	0	38(32–43)
Zone 4	6	2(tr–3)	1(0–3)	30(23–37)	67(58–72)	tr(0–1)	39(21–56)	7(4–10)	0	33(19–44)
Section F										
Zone 7	3	4(1–5)	tr(0–1)	40(28–47)	56(47–71)	tr(0–tr)	5(3–6)	6(5–8)	0	54(52–55)
Zone 6	2	5(1–9)	1(—)	29(—)	65(61–71)	tr(0–tr)	8(6–9)	8(6–9)	0	47(45–49)
Zone 4	5	4(tr–12)	4(1–13)	37(29–47)	54(46–74)	tr(0–1)	15(4–28)	10(3–16)	tr(0–tr)	47(40–59)
Section G										
Zone 7	4	2(1–3)	1(—)	39(29–50)	58(46–69)	tr(0–1)	2(tr–8)	6(2–13)	tr(0–tr)	60(55–63)
Zone 6	4	4(1–5)	1(tr–2)	37(9–50)	58(44–85)	tr(0–tr)	2(1–5)	9(6–11)	0	49(45–52)
Transition	4	2(tr–3)	1(tr–2)	43(33–50)	54(45–63)	0	4(1–8)	8(5–10)	0	52(43–62)
Zone 4	7	2(tr–5)	1(tr–3)	27(16–37)	70(59–78)	1(0–2)	14(1–38)	10(4–14)	0	43(22–52)
Section H										
Zone 2	1	tr(—)	tr(—)	49(—)	51(—)	0(—)	23(—)	10(—)	0	32(—)
Zone 1	6	1(0–3)	tr	36(17–50)	63(47–83)	1(tr–2)	43(32–51)	7(5–12)	tr(0–tr)	29(27–32)
Section J										
Zone 4	2	6(2–10)	3(1–4)	30(17–44)	61(42–80)	1(tr–1)	18(15–21)	10(5–14)	0	40(34–47)
Zone 3	4	5(4–6)	1(tr–2)	24(17–34)	70(59–77)	tr(0–1)	63(59–71)	5(4–7)	0	23(16–29)
Zone 2	3	tr(tr–1)	tr(0–tr)	54(43–61)	46(39–56)	1(0–2)	24(20–29)	9(6–12)	0	29(28–31)
Zone 1	4	3(1–6)	tr(0–1)	48(41–50)	49(47–52)	1(0–2)	39(35–43)	10(7–13)	0	18(14–20)
Section K										
Zone 2	4	1(tr–2)	0(—)	63(55–68)	36(32–44)	1(0–1)	17(15–20)	10(5–15)	tr(0–tr)	33(25–34)
Section L										
Zone 6	3	6(5–7)	tr(—)	58(58–59)	36(35–36)	1(0–1)	6(5–7)	17(12–21)	0	28(20–34)
Zone 4	2	2(tr–4)	tr(—)	38(—)	60(58–62)	1(0–1)	24(—)	8(4–11)	0	32(26–38)
Zone 3	10	5(1–15)	1(0–3)	17(5–34)	77(60–91)	tr(—)	72(45–87)	3(1–8)	0	12(5–24)
Section M										
Zone 7	5	9(1–25)	5(1–17)	33(29–41)	53(34–59)	1(0–1)	4(2–6)	10(5–16)	0	47(40–51)
Zone 6	3	2(—)	2(1–2)	50(—)	46(46–47)	1(0–2)	5(4–7)	8(3–11)	1(0–1)	39(37–40)
Zone 4	1	19(—)	0	50(—)	31(—)	0	37(—)	7(—)	0	22(—)
Section N										
Zone 6	2	4(1–7)	1(—)	51(42–60)	44(32–56)	0	9(8–10)	6(5–6)	0	34(26–42)
Zone 3	2	2(1–2)	1(0–3)	30(23–37)	67(59–75)	tr(—)	60(—)	3(—)	0	14(13–16)
Section PQ										
Zone 8	3	2(0–5)	0	29(28–29)	69(66–71)	1(0–1)	25(19–32)	6(5–6)	0	31(30–31)
Zone 7	4	4(1–7)	tr(0–tr)	40(34–47)	56(47–65)	tr(0–tr)	10(5–14)	17(10–22)	0	44(41–53)
Zone 5	4	4(0–7)	1(0–1)	33(23–44)	62(48–69)	1(0–2)	53(44–60)	5(3–7)	0	20(18–26)
Zone 4	4	9(4–13)	1(tr–2)	56(53–63)	34(32–36)	tr(0–1)	13(5–20)	7(6–9)	0	44(33–50)
Zone 3	5	8(0–29)	1(0–2)	20(9–44)	71(48–91)	tr(0–1)	71(56–88)	5(2–9)	0	13(6–17)
Section O										
Zone 9	3	2(—)	tr	23(—)	75(—)	tr(tr–1)	65(64–68)	5(4–6)	0	14(13–16)
Zone 7	8	5(1–9)	1(0–3)	42(23–50)	52(47–67)	1(0–4)	2(0–6)	14(7–17)	0	44(36–50)
Section R										
Zone 9	4	3(1–6)	tr(0–1)	28(23–33)	69(66–72)	1(tr–1)	54(38–70)	2(0–5)	0	24(18–30)
Zone 7	4	6(3–14)	6(2–11)	48(45–50)	41(34–50)	tr(0–tr)	1(0–3)	19(17–21)	0	50(40–57)

second minimum count, third maximum count on an observed specimen)

	Non-opaque minerals recomputed to 100%									Ratio Opaque to Non-opaque Mines
Garnet	Glauco-phane	Kyanite	Rutile	Silli-manite	Sphene	Staurolite	Tourma-line	Zircon	Zoisite	
13(8–20)	tr(0–1)	1(0–1)	1(0–1)	tr(0–tr)	10(7–12)	1(0–2)	1(tr–2)	4(tr–9)	1(0–2)	.82
22(—)	0	tr(—)	1(—)	0	8(—)	3(—)	1(—)	2(—)	0	1.11
16(12–22)	0	tr(0–1)	tr(0–1)	0	16(8–25)	1(tr–2)	1(1–3)	4(0–11)	0	1.18
8(4–14)	0(0–tr)	tr(0–1)	0(0–1)	tr(0–tr)	7(4–12)	1(0–3)	1(0–2)	1(0–4)	tr(0–2)	.37
11(4–26)	tr(0–1)	tr(0–1)	1(0–1)	tr(0–1)	12(5–20)	1(0–2)	1(0–3)	1(0–3)	tr(0–1)	.92
19(16–23)	0	1(0–1)	1(0–1)	tr(0–1)	19(14–23)	1(1–2)	tr(tr–1)	2(tr–6)	1(—)	.78
15(13–16)	0	tr(0–tr)	1(0–1)	tr(0–tr)	12(10–13)	1(tr–1)	1(0–1)	2(1–2)	0	.47
6(2–9)	tr(0–tr)	1(0–3)	1(0–3)	0	7(5–12)	tr(0–tr)	1(0–3)	2(1–3)	0	.40
15(8–22)	0	1(0–2)	tr(0–2)	tr(0–tr)	14(7–19)	1(0–2)	2(tr–2)	3(0–10)	2(0–4)	.88
16(14–17)	tr(0–tr)	tr(0–1)	tr(0–tr)	0	10(8–11)	2(—)	1(—)	4(2–6)	tr(0–tr)	1.18
32(24–40)	0	tr(0–tr)	1(1–2)	tr(0–1)	7(4–9)	1(1–2)	tr(0–tr)	10(8–12)	0	1.56
10(7–15)	0	tr(0–1)	1(0–1)	tr(0–tr)	7(4–11)	1(0–1)	1(0–2)	1(—)	tr(0–1)	.45
16(15–17)	0	tr(0–tr)	1(tr–2)	tr(0–tr)	14(11–17)	1(0–2)	1(tr–2)	1(tr–2)	1(tr–1)	.71
22(—)	0	tr(0–tr)	tr(0–tr)	0	12(10–14)	1(—)	0	1(0–1)	tr(—)	.45
12(9–15)	tr(0–1)	tr(0–1)	1(0–3)	0	10(5–12)	1(0–2)	1(tr–4)	1(0–4)	1(0–1)	.69
15(7–22)	0	tr(0–1)	1(0–1)	0	12(10–14)	0	1(tr–2)	2(tr–1)	1(0–2)	.67
24(20–30)	0	tr(0–1)	tr(tr–1)	0	11(9–13)	1(0–2)	1(0–2)	3(2–4)	tr(0–1)	.64
16(12–19)	0	tr(0–1)	1(0–2)	0	15(10–19)	1(0–2)	1(0–2)	2(0–2)	tr(0–tr)	.80
15(7–27)	tr(0–1)	tr(0–1)	1(0–1)	tr(0–tr)	14(10–23)	1(0–2)	1(0–3)	1(0–4)	tr(0–1)	.39
19(—)	0	0	1(—)	0	12(—)	1(—)	tr(—)	1(—)	1(—)	.96
11(8–15)	0	tr(0–tr)	1(tr–1)	tr(0–tr)	5(3–8)	1(tr–2)	1(tr–2)	1(tr–2)	tr(0–2)	.57
14(9–18)	0	1(0–1)	1(—)	tr(0–tr)	11(7–16)	1(—)	1(0–1)	1(—)	1(—)	.49
6(4–7)	tr(0–tr)	tr(0–1)	tr(0–tr)	0	3(2–6)	tr(0–tr)	tr(0–tr)	tr(0–1)	tr(0–1)	.34
14(10–18)	0	1(1–2)	tr(0–tr)	0	17(14–20)	1(tr–1)	3(1–5)	tr(0–1)	1(tr–1)	1.17
12(10–14)	0	1(tr–2)	1(tr–1)	0	13(9–16)	1(tr–2)	2(2–3)	tr(0–tr)	1(tr–1)	.98
17(15–20)	tr(0–1)	1(0–1)	tr(0–1)	0	15(11–19)	1(tr–1)	2(tr–3)	3(1–4)	tr(tr–1)	1.75
20(15–22)	1(0–2)	2(0–3)	tr(0–1)	0	20(13–27)	1(0–2)	2(1–3)	1(0–4)	2(1–3)	1.60
20(18–24)	tr(0–tr)	1(0–1)	2(tr–5)	0	9(6–11)	1(tr–1)	tr(—)	2(tr–3)	tr(tr–1)	.63
5(1–17)	tr(0–tr)	tr(0–1)	tr(0–1)	0	5(2–14)	1(0–2)	tr(0–tr)	1(0–4)	tr(0–1)	.22
17(13–20)	tr(0–tr)	1(0–1)	1(0–1)	0	15(12–18)	2(0–2)	2(tr–4)	2(tr–2)	1(—)	.62
22(21–24)	0	tr(0–1)	1(—)	tr(0–1)	12(11–15)	2(1–3)	2(1–3)	5(2–9)	tr(0–1)	1.11
22(—)	0	0	0	0	7(—)	0	2(—)	2(—)	0	1.61
24(—)	0	1(0–1)	tr(—)	0	19(17–22)	1(0–2)	1(tr–2)	5(tr–10)	0	1.16
11(—)	0	tr(0–tr)	tr(—)	0	9(7–10)	1(0–2)	1(—)	1(0–2)	tr(0–tr)	.45
23(19–28)	0	1(tr–1)	tr(—)	0	8(7–11)	2(1–3)	1(1–2)	2(tr–4)	tr(0–tr)	.42
13(11–14)	1(0–1)	tr(tr–1)	tr(tr–1)	0	11(7–14)	1(tr–1)	1(0–2)	1(0–2)	1(0–2)	.71
9(7–11)	0	1(—)	0	0	8(7–9)	1(0–2)	1(0–3)	1(0–3)	tr(0–2)	.53
18(11–24)	0	tr(0–1)	1(0–1)	tr(0–tr)	11(8–15)	1(0–1)	1(0–2)	5(tr–12)	tr(0–2)	1.65
5(1–9)	tr(0–tr)	tr(0–tr)	tr(0–tr)	0	5(2–9)	tr(0–1)	1(0–1)	tr(0–1)	tr(0–1)	.29
10(7–13)	0	0	tr(0–1)	0	4(3–6)	1(tr–1)	tr(0–tr)	tr(0–1)	0	.31
16(11–19)	tr(0–tr)	1(1–2)	tr(tr–1)	0	17(13–23)	1(0–3)	1(0–2)	2(1–2)	tr(0–1)	.81
10(8–12)	0	tr(0–1)	tr(0–1)	0	5(3–7)	2(0–4)	1(0–2)	tr(tr–1)	0	.41
14(11–22)	tr(0–1)	tr(0–tr)	tr(0–1)	tr(0–1)	12(11–13)	1(0–1)	2(0–3)	1(0–2)	0	1.17

less; (2) brown, absorption Z>Y>X, Z=greenish brown to brown, Y=brown, X=straw; (3) green, absorption Z>Y>X, Z=dark bluish green, Y=green, X=green, extinction angle Z∧c=18°. Colorless amphibole occurs sparingly throughout the area. The brown amphibole is characteristically associated with weathered bentonitic sands. In section P, an anomalous biaxial figure with a moderate 2V.

Epidote occurs in euhedral, in angular, and in rounded grains. The pleochroism is: X=Z=colorless to pale yellow, Y=bottle green. The euhedral grains are very transparent, but the rounded ones are often dusky. Clinozoisite resembles epidote, but is colorless and positive, and

TABLE 2. *Representative Mineral Frequencies*

Zones	1	2	3	4	5	6	7	8	9
Andalusite	1	1	tr	1	1	1	1	1	1
Colorless	R	R	R	R	R	R	R	R	R
Pleochroic	R	R	R	R	R	R	R		R
Amphibole	41	22	66	21	53	7	4	25	55
Green; greenish brown	C	C	C	C	C	S	S	C	C
Colorless	R	R	R	R	R	R	R		R
Clinozoisite	8	10	4	8	5	8	11	6	5
Corundum	0	0	0	0	0	tr	tr	0	tr
Epidote	24	32	15	38	20	40	51	31	21
Detrital	C	C	C	C	C	C	C	nd	C
Authigenic	S	S	C	S	S	S	C	nd	S
Garnet	12	17	8	16	9	23	15	23	9
Colorless	R	S	C	C	R	S	S	S	S
Yellow	R								
Pink	C	C	R	S	C	C	C	C	S
Salmon, brown	S	S	R	R	S	S	S	S	R
Glaucophane	0	tr	tr	tr	0	tr	tr	0	tr
Kyanite	tr	1	tr	tr	1	1	1	1	tr
Rutile	1	tr	tr	1	tr	tr	tr	tr	tr
Sillimanite	0	0	0	tr	0	tr	tr	0	tr
Sphene	9	11	5	11	8	12	13	8	6
Colorless round	R	S	R	R	R	R	R	R	R
Colorless euhedral	R	R	R	S	R	S	S	R	R
Brown round	R	S	R	S	S	S	S	S	S
Honey	C	C	S	S	S	C	R	S	S
Brown pleochroic	S	R	R	R	R	R	R	R	R
Staurolite	1	1	1	1	1	1	1	2	1
Tourmaline	2	2	1	1	1	1	1	1	1
Brown	R	R		R		R	R		S
Blue	R	R		R		R	R		R
Greenish brown	S	S	S	S	R	S	S	R	R
Pinkish brown	R	S	R	S	R	R	R	R	S
Colorless, Incl.	R	R		R		R	R		S
Zircon	1	1	1	2	1	2	2	2	1
Colorless	S	S	S	S	S	S	S	S	S
Red pleochroic	R	R	R	R	R	R	R	R	R
Zoisite	tr	1	tr	tr	tr	tr	1	tr	tr

C=common, above 8%; S=sparse, 1 to 8%; R=rare, 0–1%; C/S or S/R, the first mineral more abundant than the second; C/R the first mineral very much more abundant than the second.

in the bentonitic sands above the ash beds, brown amphibole forms up to 90% of the non-opaque minerals. In other environments it is a sparse constituent. The green amphiboles are dominant wherever else amphiboles are reported.

Clinozoisite (see Epidote).

Corundum occurs as fragments, basal plates, and twinned crystals. Fragments and twinned crystals appear mottled yellow due to an uneven depth of color. The basal plates are colorless or pale blue. Most of these are uniaxial, but some give zoisite is differentiated by anomalous blue interference colors.

The garnet has various shapes and colors. Yellow oblong garnets with hackly surface occur only in zone 1. Brown trapezahedron-dodecahedrons occur sparingly, but especially in zone 6, where they are associated with other colored garnets. Clear pink, angular to subangular garnets with conchoidal fracture are the common type in many zones, but are subordinate to the colorless garnets in zones 4 and 5. In zones 6, 8 and 9 some of the pink

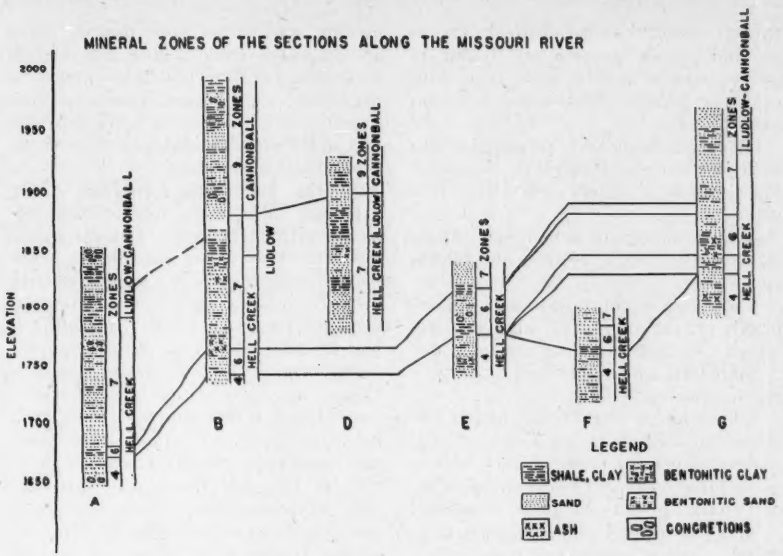
MINERAL ZONES OF THE SECTIONS ALONG THE MISSOURI RIVER
ELEVATION
2000
1950
1900
1850
1800
1750
1700
1650
A
B
D
E
F
G
HELL CREEK
LUDLOW-CANNONBALL
LUDLOW
CANNONBALL
9 ZONES
7 ZONES
LEGEND
SHALE, CLAY
SAND
ASH
BENTONITIC CLAY
BENTONITIC SAND
CONCRETIONS

FIG. 2.

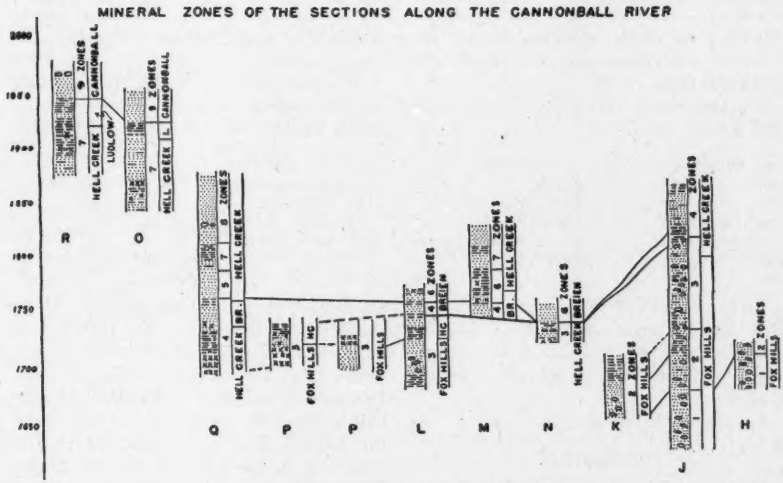
MINERAL ZONES OF THE SECTIONS ALONG THE CANNONBALL RIVER
R
O
Q
P
P
L
M
N
K
J
H
HELL CREEK
FOX HILLS

FIG. 3.

garnets are well rounded and dusky. Salmon and brown garnets are found in greater numbers with pink than with colorless garnets. Inclusions are commonly present.

Glaucophane occurs in prismatic grains with vertical striations (110 cleavage). Pleochroism: Z = blue, Y = violet, X = pale blue.

Kyanite occurs in subangular prisms showing (010) and sometimes (001) cleavage.

Rutile occurs in brown and yellow-brown prisms and twins, and, less frequently, in dark red platy grains.

Sillimanite is characterized by parallel and interlacing fibers.

Sphene has several crystal habits and colors. Most common is a honey-colored, slightly pleochroic type, which is oblong or irregular in shape. Locally common are dull dark brown irregular, rounded, or diamond-shaped grains; transparent, round, colorless grains; and transparent, colorless to straw-colored ones. Least common is the strongly pleochroic brown to yellow sphene.

Staurolite is oblong or irregularly shaped, and has either a hackly or a conchoidal fracture. Pleochroism is in shades of yellow, or rarely, chestnut brown. Inclusions are commonly present in the prismatic form.

Tourmaline is varied in crystal habit and color.

Epsilon	*Omega*	*Habit*
brown	black	prismatic, round
blue, gray	blue, gray	basal fragments
greenish brown	brown to black	prismatic, round
pinkish brown	green, brown, black	prismatic, round
colorless, pale green	brown	prismatic, contains small opaque inclusions

Zircon occurs predominantly in colorless, doubly terminated prisms, and in colorless, well rounded grains. Rarely are round red, slightly pleochroic rounded grains.

Zoisite (see Epidote).

CORRELATION

On the basis of heavy mineral frequencies of green and brown amphiboles, epidote, and garnet, nine mineral zones are proposed. Table 3 gives the relative percentages of these minerals, in terms of total non-opaque heavy minerals, and the localities and beds sampled, while figures 2, 3, and 4 give schematic correlation between sections and zones.

In the Fox Hills formation, three lithologic units were noted. These coincide with three heavy mineral zones: (1) The lowermost horizon of thick bedded, yellowish brown sandstone with brown concretions and Halymenites corresponds to zone 1 (cf. p. 133, section J, bed 1). The average amphibole content for this zone is 41%. (2) The intermediate horizon of yellow to olive colored sandy, banded shale is represented by zone 2 (cf. p. 133, section J, bed 2), in which the average amphibole content has fallen from 41% to 22%. (3) The upper horizon of gray white sandstone with concretions corresponds to most of zone 3 (cf. p. 133, section J, beds 4–7). There is a decided increase in the amount of amphibole, from 22% to 66%, and a decrease in the other heavy minerals.

The high amphibole count of the Fox Hills continues into the Hell Creek, above the lignitic shale marking the boundary, to the base of the Breien (cf. p. 133, section L, bed 2; p. 134, section L, beds 3–6).

The Hell Creek is divided into a series of alternating beds of brown lignitic shale, weathered bentonite, and massive sands with zones of shale partings. Along the Missouri River, the Fox Hills is not exposed. Zone 4 occurs in the sands and shales below the first bentonitic bed (cf. p. 133, section B, bed 1). Along the Cannonball River, zone 3 extends to the base of the Breien. The lowermost bed in the Breien is a fine-grained, brown, badly weathered sand, with limonitic concretions and Halymenites (cf. p. 134, section

TABLE 3. *Correlation*

Zone	Locality	Bed[1]		Amphibole	Epidote	Garnet
1	H			43	29	11
1	J	(1)		39	18	12
			Average	41	24	12
2	H			23	32	19
2	J	(2)		24	29	14
2	K			17	33	17
			Average	22	32	17
3	J	(4–7)		63	23	6
3	L	(2–6)		72	12	5
3	N			60	14	11
3	P			71	13	5
			Average	66	15	8
4	A			18	37	16
4	B	(1)		15	48	15
4	E			39	33	10
4	F			15	47	12
4	G			14	43	15
4	J	(10)		18	40	14
4	L	(8)		24	32	20
4	M	(1)		37	22	22
4	Q			13	44	18
			Average	21	38	16
5	PQ			53	20	9
			Average	53	20	9
6	A			11	40	22
6	B	(1)		5	45	19
6	E			7	38	32
6	F			8	47	22
6	G			2	49	24
6	L	(8)		6	28	20
6	M	(1–7)		5	39	22
6	N			9	34	24
			Average	7	40	23
7	A			2	55	13
7	B	(2–6)		1	61	11
7	D			3	46	15
7	E			8	49	16
7	F			5	54	16
7	G			2	60	15
7	M	(7–9)		4	47	17
7	Q			10	44	13
7	O			2	44	16
7	R	(1–4)		1	50	14
			Average	4	51	15
8	Q			25	31	23
			Average	25	31	23
9	B	(8–11)		49	25	8
	D			54	20	6
	O			65	14	10
	R	(5)		54	24	10
			Average	55	21	9

[1] In sections described in the text, the numbers after the locality refer to the beds from which the samples were collected.

L, beds 7 and 8). This corresponds to zone 4. There is a decrease in amphibole count from 66% in zone III to 21% in zone 4.

Above zone 4 is a dark gray limonitic shale followed by a fine-grained to silty, gray-green sand and bentonite which mark the beginning of zone 6 (cf. p. 134, section L, beds 9–12).

Zone 6 is differentiated from zone 4 by a decrease in amphiboles from 21% to 7%, and by a change in the character of garnets, from predominantly colorless to predominantly colored. Zone 6 extends above the Breien member.

Zones 6 and 7 are differentiated particularly on the basis of their epidote and garnet count. Zone 7 extends through most of upper Hell Creek, and to the top of the Ludlow. In zone 6, garnet is above 20%. The average amount of epidote is 40%, with the count slightly above average in the sections along the Missouri River and below average along the Cannonball River (cf. p. 133, section B, bed 1 and p. 134, section M, beds 2–7). It may be expected that sections closer together, will be more like each other.

Zone 7 shows a decrease in the amount of garnet, from 23% to 15%, and an increase in epidote from 40% to 51%. Again the sections along the Missouri River contain more epidote than the sections along the Cannonball River, but the trend is to increase in epidote in zone 7.

The Ludlow consists almost entirely of lignitic shales. Narrow sand beds could not be differentiated from the Hell Creek beds in zone 7.

Zones 5 and 8 are local at Q.

There is a marked change in heavy mineral content at the base of the Cannonball formation. The amphibole content increases from an average of 4% in zone 7 to 55% in zone 9, with greater quantities of amphibole nearer the contact than higher up.

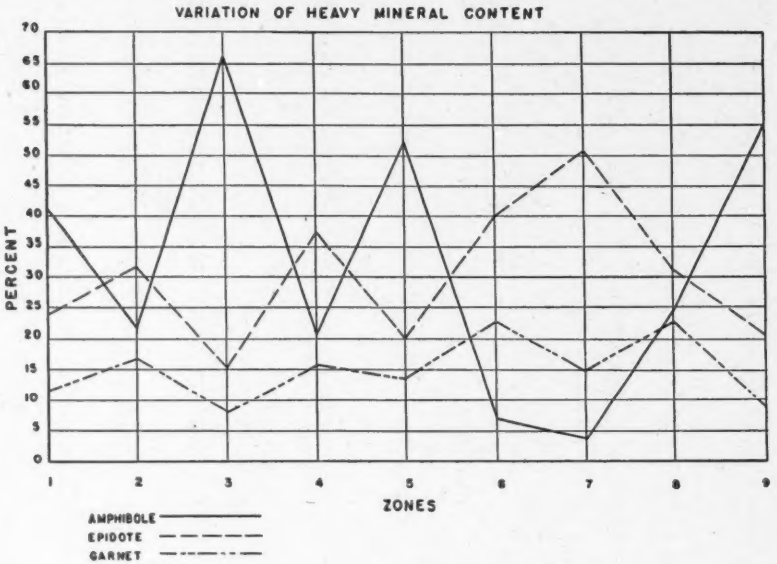

FIG. 4.

SUMMARY

A study of a restricted area in Morton and Sioux Counties, North Dakota, was made to correlate various exposures of Fox Hills, Hell Creek, Ludlow, and Cannonball sediments. Nine mineral zones were established. In the marine Fox Hills and marine Cannonball sediments, the zones were characterized by a large quantity of amphibole. The amphibole diminishes in amount in the lower Hell Creek, and, except at one locality, Q, amphibole is insignificant in upper Hell Creek. Epidote, sphene and garnet are the significant minerals in the Hell Creek and Ludlow sediments.

ACKNOWLEDGMENTS

The author is indebted to the North Dakota Geological Survey for providing for field expenses, without which this work could not have been undertaken. Dr. Wilson Laird, State Geologist, directed the field work and contributed valuable information of the stratigraphy and areal geology. To Miss A. Swineford of the Kansas Geological Survey special thanks are due for accompanying the author in the field.

Dr. J. L. Anderson of the Department of Geology of the Johns Hopkins University gave material direction in the laboratory studies and in the preparation of the mineral charts. The Geological Laboratory of the Johns Hopkins University furnished the materials used in making the heavy mineral analyses.

Field and laboratory studies were carried on during the summer of 1942.

The paper was critically read by Dr. Paul Krynine, Pennsylvania State College, and Dr. C. S. Ross and Dr. H. D. Miser, United States Geological Survey.

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AN INTERESTING MISSISSIPPIAN BRECCIA

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The purpose of this paper is to describe an unusual limestone breccia which occurs in the foundation of Hales Bar Dam (built in 1905–1913 by a private power company) on the Tennessee River. The foundation consists of nearly flat-lying, pure, massive Bangor limestone (Mississippian) averaging better than 95 per cent calcium carbonate. The cavernous and weathered condition of the rock caused considerable trouble in securing the dam foundation at the time of construction and resulted in water passing beneath the dam as soon as the reservoir was filled. Various programs, designed to stop this leakage, were attempted during the 26 years between completion of the structure and its acquisition by the Tennessee Valley Authority. Although the total cost of these programs amounted to several million dollars, none was successful.

In 1940, the Authority started a program of grouting combined with a cut-off[1] wall to stop the leakage under the dam. All visible signs of leakage from the 13 boils in the tailwater have now been eliminated and the project is virtually completed. The cut-off wall was made by drilling 18-inch diameter holes, so spaced that they intersected one another, through the rock along the upstream face of the dam. When each hole was lined with asbestos-cement pipe and filled with concrete the series formed an 18-inch wall across the cavernous areas.

All core recovered from the diamond drill and the large-diameter drill holes has been carefully logged. From these logs, lithologic characteristics and minor structural details can be determined.

One bed of particular interest warrants description. This bed is a limestone breccia 0.5 to 1.5 feet thick which overlies a calcarous shale 0.5 to 3.0 feet thick. The matrix of the breccia is a medium gray, dense limestone which is quite soft. The brecciated fragments themselves are very dark gray, dense, hard limestone, more than an inch thick. Sometimes two fragments can be fitted together, showing that they have been broken apart *in situ* (fig. 1).

Ordinarily the breccia zone is nearly

[1] Schmidt, L. A., Jr., 1943. "Flowing Water in Underground Channels, Hales Bar Dam, Tennessee," *Proceedings, Am. Soc. Civil Engineers*, pp. 1417–1446.

TABLE 1.—*Chemical analyses*

	1	2	3	4	5
Silicon Dioxide (SiO_2)	4.11%	10.44%	3.82%	4.82%	2.71%
Aluminum Dioxide (Al_2O_3)	0.87	2.09	—	—	0.84
Ferric Oxide (Fe_2O_3)	1.08	1.56	0.62	0.65	0.48
Calcium Oxide (CaO)	31.57	29.85	32.27	34.29	30.30
Magnesium Oxide (MgO)	18.39	16.43	18.11	15.94	20.99
Loss on Ignition 100° to 1000° C.	43.74	39.34	—	—	45.35
Calcium Carbonate ($CaCO_3$), calculated	56.34	53.27	57.62	61.24	54.17
Magnesium Carbonate ($MgCO_3$), calculated	38.46	34.36	37.88	33.33	43.90

1. Brecciated fragments in Bangor limestone, Hales Bar Dam.
2. Matrix of breccia, Hales Bar Dam.
3. Knox dolomite, post-Nittany, near Whitwell, Tennessee.
4. Knox dolomite, Copper Ridge, East Chattanooga, Tennessee.
5. Knox dolomite, Copper Ridge, Chickamauga Dam, Tennessee.

flat-lying, as is the rest of the rock beneath the dam. Occasionally, however, the zone has small asymmetrical folds accompanied by contortion of the underlying shale. The general aspect of these folds and their restriction to these two beds seem to indicate that some movement took place before the sediments were consolidated. The angularity of the fragments, evidence of fracturing *in situ*, and the probability of movement would seem to indicate that the breccia was an intraformational conglomerate. However, it was noted that the lithology of

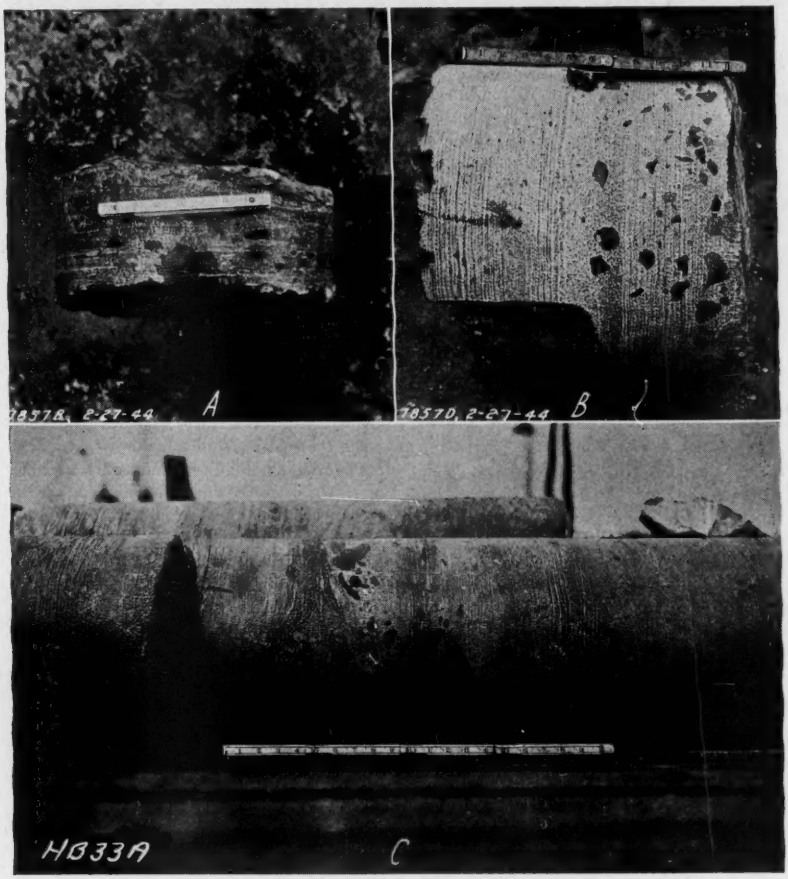

FIG. 1.—Samples of breccia (core 15-inch diameter)
A. Breccia
B. Breccia (bottom at right)
C. Breccia and underlying shale

the breccia differed greatly from that of any other rock in the vicinity. Chemical analyses were therefore made which show these fragments to be a dolomitic limestone of the same composition as the Knox dolomite. In fact, the chemical characteristics are so similar, and at the same time so different from any other known formation in this vicinity, that the Knox must be taken as the origin of this breccia. The matrix of the breccia has the same composition as the fragments except for larger proportions of silica and alumina. This shows weathering of the fine particles of the sediment.

TABLE 2.—*Variation of Percentages in Twelve Samples of Knox Dolomite*

SiO_2	0.36–11.37%
Al_2O_3	0.16– 2.37
Fe_2O_3	0.38– 1.20
CaO	27.61–37.44 ($CaCO_3$ 49.27–66.85%)
MgO	14.79–21.40($MgCO_3$ 26.75–44.74%)

The implication is that the breccia was derived from broken fragments of the Knox which was elevated to the surface at some point in southeastern Tennessee for a very brief period during Mississippian time. Inasmuch as the matrix indicates some weathering, it may be further inferred that the Knox must have actually risen above sea level.

This author is not aware of any evidence of such an uplift, and he would be temerarious to base a new theory of the diastrophic history of this region on this one occurrence. Nevertheless, the coincidence of the chemical composition is so striking as to warrant re-examination of our present evidence and examination of new evidence with the possibility of a brief local uplift in mind.

REVIEW

RUSSELL, R. J. *Lower Mississippi Valley Loess.* Geol. Soc. America, Bull., vol. 55, pp. 1–40, 1944.

In a paper entitled "Lower Mississippi Valley Loess" R. J. Russell discusses certain silt deposits in the highly dissected bluffs of the region stated. In giving a definition of *loess* he departs from commonly accepted custom which is to include eolian origin as an essential quality. Instead he desires to make the definition purely lithological. He thinks that the term should include materials with "the following essential characteristics: Loess is unstratified, homogeneous, porous, calcareous silt; it is characteristic that it is yellowish or buff, tends to split along vertical joints, maintains steep faces, and ordinarily contains concretions, and snail shells." Russell goes on to say that, "The writer estimates that over half of the American literature on loess actually refers to loesslike terrace silts." He regards the ordinary mapping of a belt of loess along the east bluffs of the lower Mississippi River as an error for "only a minute portion of the Loess Hills is actually covered." The deposits to which Russell confines the term loess are confined to slopes below all but the lowest of the Quaternary terraces; nowhere do they reach the level of the highest terrace. Modern road grading has disclosed the fact that earlier writers confused vertical range of loess with actual thickness. Cuts through divides show a "pseudoanticlinal" structure, the loess mantling both sides of the ridge regardless of its direction.

Russell concludes that loess has 50 to 75 per cent by weight of its particles in the range from 0.01 to 0.05 mm. diameter. The following characteristics he regards as nonessential: color, vertical jointing, vertical exposures, tubular structure, incrustations, concretions, healing of fractures, gravel beds, and the peculiar erosional features. The dominance of terrestrial forms in the fauna is recognized, although there are some fresh water snails. It was discovered that vertebrate remains are confined to terrace deposits and are absent in the loess.

In considering the origin of the loess Russell demonstrates that it is not a part of the stratigraphic sequence of the Coastal Plain, for it is confined to slopes which truncate the beds of

the older formations. He regards the backswamp phase of the terrace deposits as the parent material from which the loess has been derived. These deposits are calcareous and have a greater range of sizes of particles than does loess. No mechanical analyses of these clays are given. The latter is "too uniform to be the result of direct deposition from a current." Prerequisites for loess formation are: (1) backswamp deposits in adjacent terraces, and (2) deep dissection. He argues: "Against eolian origin it may be urged that no actual or hypothetical directions of winds could account for its distribution" and the loess has "The shape of a deposit that is ordinarily assumed by colluvial materials."

Characteristics which Russell regards as essential to loess include: calcareous content, a change to greater uniformity of grain size than in the parent material, a "partial sifting process" due mainly to removal of small particles leaving large ones, porosity, and relative competence due to cementation. He thinks that the snail shells are not primary fossils but were introduced partly by falling into cracks but mainly by mass movement. These animals throve on calcareous soil and their shells could only be preserved in calcareous deposits. Russell ascribes the uniform texture of loess to loss of finer particles in the upper part of the soil profile developed in the river silts. This process is "intensified by churning movements" during colluvial creep. Calcium carbonate is dissolved from the parent material and redeposited in the "lower parts of colluvial slopes" in "materials advanced far in loessification." There it retards creep and preserves the snail shells which were incorporated during soil movement. He fails to state what becomes of the finer particles and does not consider flocculation into larger particles. The fact that the outcrops of gravel beds where ground waters are escaping are being cemented with calcium carbonate is cited as evidence that calcification does take place to some extent under existing climatic conditions. However, as calcium carbonate is not now accumulating in the soil Russell is forced to ascribe the process of calcification to "soil climate aridity." He thinks that such conditions occurred when sea level was low and before the present post-Wisconsin alluvial fill was deposited. Then the water table under the bluffs was much lower than it now is. He rejects the idea that a semi-arid climate was once present in the lower Mississippi Valley, saying: "Nothing short of a high transverse mountain barrier" could shut out the warm moist air masses from the Gulf of Mexico which bring the rains of today. Instead, he thinks of *loessification* taking place during the several glacial maxima.

It is in the "application of conclusions to loess in other regions" that the reviewer takes issue with Russell. It is true that Russell admits that such extension is hazardous but he holds, "If the conclusions are sound, however, to deny their universal application is possibly unwarranted conservatism." Judging from the discussion following the above statements, Russell can never have seen the loess deposits of the upper Mississippi Valley. The reviewer has worked in that region for many years and feels competent to disagree most strongly. The northern loess is a mantle which covers flat plains, high uplands, and slopes alike. In some districts it rests on highly altered glacial till, whereas in others it lies on residual deposits formed from bed rock, and in some localities it rests upon unaltered glacial drift. Over a large part of its distribution there are two loesses, the older of which was deeply weathered before the deposition of the younger one. The loess has a soil profile of its own and was originally derived from unweathered materials. Leached loess, however, has many of the characteristics of the unaltered material. Followed to the west into Nebraska the loess becomes progressively coarser and is obviously situated to leeward of the sand hills. There is little loess in south-central Iowa but it is well developed along the eastern bluffs of both Missouri and Mississippi rivers including the hills of the Driftless Area. In all places the loess lies with abrupt non-transitional contact on materials such as sandstone, gumbotil, gravel, and cherty clay from which it cannot possibly have been derived. Covering much of the highest land there is no uphill source. In northeastern Iowa the loess is thin or absent on flat plains but forms belts of hills around them. For a long time that relationship was ascribed to the presence of glacial ice on the plains during loess deposition, a theory in-

compatible with the presence of snail shells in the loess. Shimek presented a rational view by suggesting that deposition was controlled by rough topography and forest in the areas marginal to the flat plains. In the Driftless Area loess is found mainly on the east sides of north-south ridges. It is absolutely impossible to ascribe a colluvial origin to all the northern loess.

Turning to Russell's original area, which the reviewer has examined only very briefly, three major points of disagreement may be raised. First, does not the intrusion of fragile snail shells into a moving colluvial mantle seem improbable? Second, the semi-aridity demanded for calcium carbonate deposition in weathered material is not in harmony with the suggested mass movement of soil on a large scale. Mud flows could bury snails but creep would be less likely to do so. Third, the droughts of the 1930s clearly show that dry weather in the lower Mississippi Valley is the result of a "mountain range." But it is a "range" of subtropical high pressure air, the Azores-Bermuda High. When this air mass invades the north shore of the Gulf of Mexico, it brings scanty rainfall. No one seems to know just why this shifting of weather conditions takes place but it seems likely that it may have taken place during some of the interglacial intervals. Low water table does not promote calcification of the soil unless there is upward movement of ground water. During glaciation the polar front must have been forced far to the south with consequent increased storminess.

In conclusion, Russell may be right in that much of the supposed loess of the lower Mississippi Valley is actually a colluvial mantle, although the fossiliferous deposits are hard to explain by such a theory. Leighton and MacClintock have shown that weathering with good subsoil drainage alters normal glacial till into *silttil*. But this process involves introduction neither of snail shells nor of calcium carbonate. It may involve flocculation of clay. Silttil is readily discriminated from loess by use of a hand magnifier for, although the silt content is high, the larger particles of the till were not destroyed. But to suggest that the loess of Nebraska, Iowa and Illinois is colluvial is totally unjustified.

The following selected references are given as they, as well as many others, were ignored by Russell.

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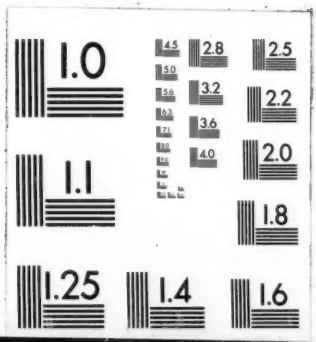
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